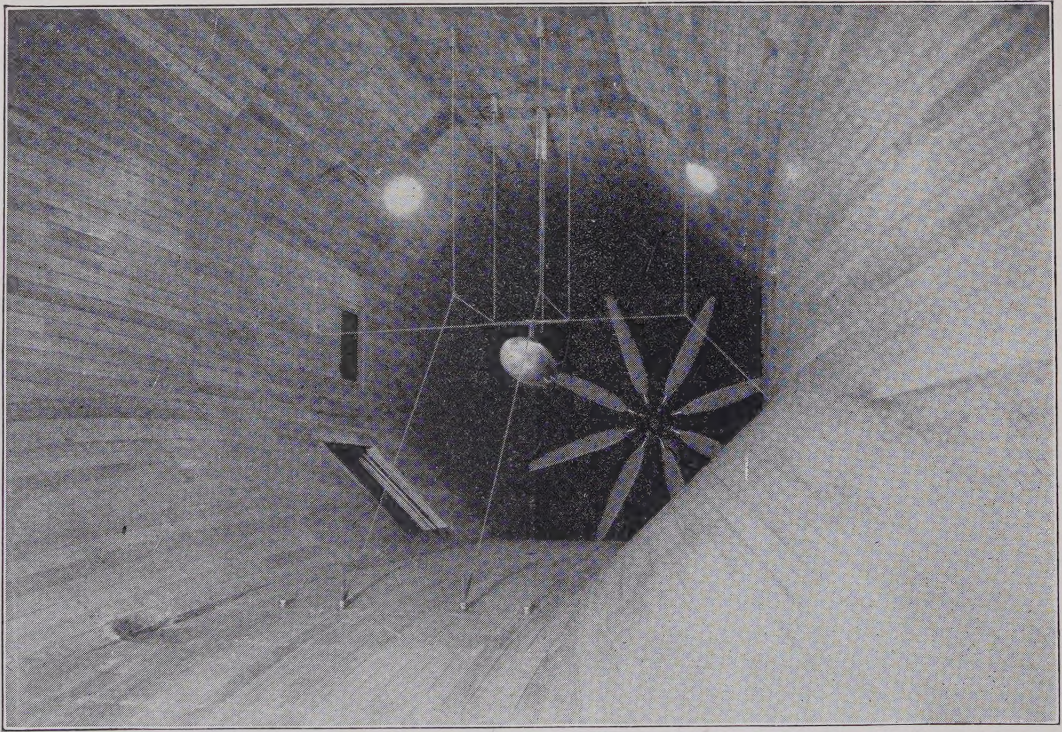
SIMPLIFIED AERO-DYNAMICS

ALEXANDER KLEMIN



Model of a Metal-Clad Airship designed by the Aircraft Development Corporation suspended for aerodynamic tests in the 9 foot Wind Tunnel of New York University.

SIMPLIFIED AERODYNAMICS

By

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PREFACE.

THERE is no doubt that a knowledge of the fundamentals of aerodynamics is essential to everyone who is already engaged in the aviation industry, or preparing to enter this industry, or who is simply learning to fly.

In some respects while the air is all-pervading, its flow and action on other bodies seems mysterious, mainly because it is invisible.

In other branches of industry, we have instinct to guide us. Flying is too recent for its understanding to be instinctive as yet, though it may in time become as instinctive as riding a bicycle.

Fortunately, aerodynamics, in its fundamentals, is surprisingly simple.

In this book, I have acted on the principle that there is no fundamental principle of aerodynamics which cannot be understood by anyone willing to take a little trouble, and provided such principles are clearly and simply set forth.

At the same time, I have not avoided mathematical symbols, because mathematical symbols very often constitute an easier method of explanation or understanding than a roundabout verbal exposition. The mathematics have been kept down to the veriest elements, however, and I have endeavored to provide such a review of the mathematics involved as may be read in a couple of hours.

The student is particularly advised to do the problems to which answers are invariably provided. In many years experience of teaching, I have found that it is possible for a student to listen to a lecture or to read a book and to grasp the subject only in appearance. The ability to do a simple problem is the touchstone of knowledge, and the mere process of doing the problem is the best way to acquire exact knowledge.

The book has been surprisingly difficult to write, much more so than an advanced text, but I have been encouraged by the hope that it would help the student in the most difficult stage, namely, the beginning.

It is impossible to avoid minor errors, in such a text, and slide-rule accuracy only has been sought in the calculations. If readers find mistakes and bring them to my notice, I shall be grateful.

My sincere thanks are due to Mr. Benjamin F. Ruffner, B. S., Instructor in Aeronautical Engineering, and to Mr. E. Schaefer and Mr. William Gauvain, senior students in aeronautics, who have given me invaluable help in preparing drawings and in calculations. Many thanks are due to Mr. George C. Chou, Aero. E., in proof reading and in preparation of the index.

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CHAPTER I

USEFUL MATHEMATICAL AND MECHANICAL PRINCIPLES

In the study of aerodynamics as applied to the airplane, only very simple formulae and ideas in mathematics, mechanics, and physics are required. It is much better for a student, even if his mathematics is quite rusty, to face these few principles boldly than to try to avoid them. Roundabout verbal explanations are far harder to understand than ideas expressed in simple mathematical language. Once this simple mathematical language is grasped, it is possible to acquire the elements of aerodynamics much more rapidly, and to apply them with ease in practical problems. In this first article we shall summarize only the most useful principles of mathematics and mechanics.

Constants

If an airplane flies at a steady speed of so many miles per hour, the distance it has flown is said to vary as the number of hours flown. This is expressed mathematically as follows: $s \propto t$ (reads varies as t) where s stands for distance in miles and t for time in hours.

To express the relation of s, t, and speed in the form of an equation, we may denote the steady speed of the airplane by V and write

$$s = Vt.$$

The point to note here is that when s varies as t, then s is equal to a constant times t. V is a constant in this case because the speed is steady.

If the speed is 60 miles per hour, then the value of the constant V is 60 and in three hours of flight, the distance flown will be $s = 60 \times 3 = 180$ miles.

It is quite important to grasp this simple idea of a constant.

Juggling with an Equation

Some of us remember algebra, as learned at school, with pain. Probably because it was taught as an abstract science. It can be quite fascinating when applied to a matter in which we are practically interested. For example in the preceding paragraph

$$s = V \times t, \text{ then } t = \frac{s}{V}, \text{ and } V = \frac{s}{t}.$$

If the airplane has flown 360 miles at 60 miles per hour, what is the time taken?

Substituting in the equation $t = \frac{s}{V}$, we get $t = \frac{360}{60} = 6$ hours.

If the airplane has flown 500 miles in 5 hours, what is the speed?

Substituting in the equation $V = \frac{s}{t}$, we get $V = \frac{500}{5} =$ 100 MPH.

We shall encounter nothing much harder than such transformations.

Problems in Geometry and Trigonometry

The height of the lowest clouds above the ground in any locality is called the "ceiling" for the locality, and it may be very important to know this in practical flying. To determine the ceiling at night a Ceiling Projector is used. This consists of a searchlight, mounted so as to throw a beam of light upward to the clouds at an angle of 45 degrees to the ground, as shown in Fig. 1.

The operator measures the distance from A to B. B is directly under the center of the spot on the cloud C. He then knows that the distance BC or the ceiling is equal to the measured distance AB. If the angle with the ground is 45° the

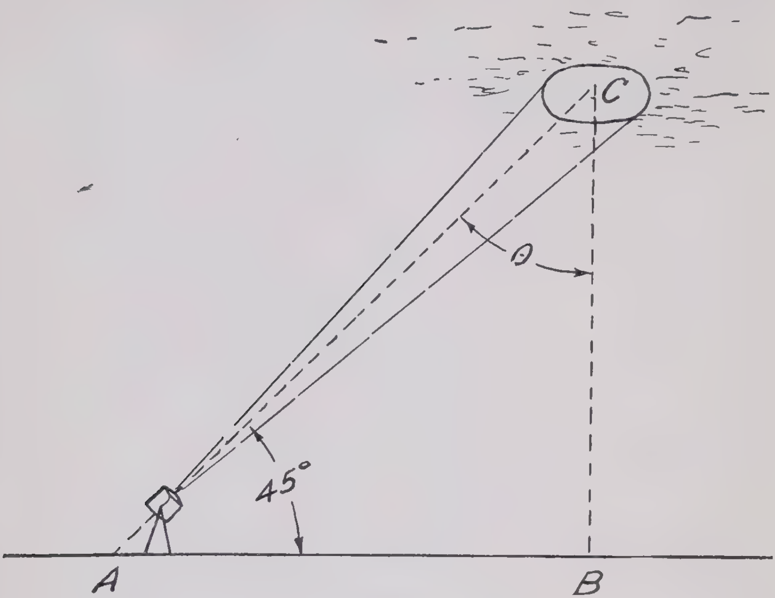


FIGURE 1

angle θ* must be 45°. This follows from the fact that the sum of the interior angles of any triangle is equal to 180°. Since the angle at B is 90° then $180 - (45 + 90) = 45°$.

We then have a triangle with two equal angles and the sides opposite the equal angle are equal.

In the example of Fig. 1 it makes no difference what the distance AB is. As long as the angle that the beam of light

* The symbol θ is a Greek letter pronounced theta. Almost all scientific articles and text books use Greek letters to denote angles and it is a great help to become familiar with them.

makes with the ground remains at 45° the distance BC will be equal to AB.

Suppose that instead of pointing the light up at 45° we pointed it up at a much smaller angle, as along the line AC of Fig. 2.

We can now see that AB is not equal to BC, so measuring AB will not of itself tell us the length of BC.

This is where trigonometry comes to the rescue. It is found that for any angle β (pronounced beta) of a right triangle the

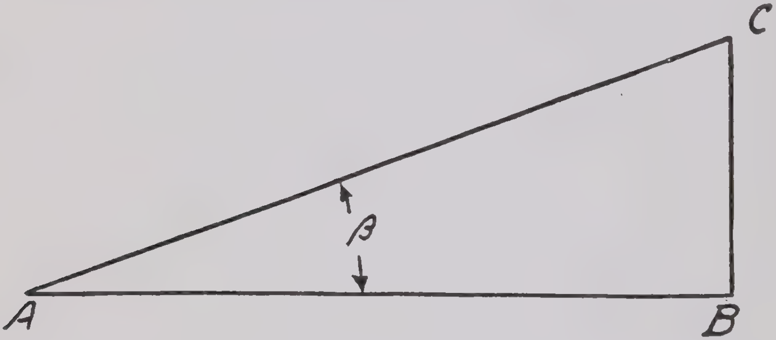


FIGURE 2

three sides of the triangle bear definite relations to one another and these relations or ratios are called natural trigonometric functions. Their values are tabulated in special tables, handbooks, and books on trigonometry.

The trigonometric functions most frequently used are the sine, cosine, and tangent, which are generally abbreviated into sin, cos, and tan, respectively.

There is nothing mysterious about these functions as they are simply the ratios that exist between the sides of a right triangle containing the angle, which of course may be any angle less than 90°.

The functions are defined as follows:

$$\sin \beta \text{ (sine)} = \frac{BC}{AC},$$

$$\cos \beta \text{ (cosine)} = \frac{AB}{AC},$$

$$\tan \beta \text{ (tangent)} = \frac{BC}{AB}.$$

In our example of the searchlight projector in Fig. 1, β was equal to 45° and BC = AB.

From this we get

$$\tan \beta = \tan 45° \doteq \frac{BC}{AB} = 1.$$

In our example of Fig. 2 we can measure AB and if we know the angle β we can find BC from the relation $\tan \beta = \frac{BC}{AB}$, or BC = AB $\tan \beta$.

If AB is 100 feet and β is 30° we have

$$BC = 100 \tan 30°, \text{ and}$$
$$\tan 30° \text{ is } 0.577.$$

Therefore BC = 100 × 0.577 = 57.7 feet.

The value of the trigonometric functions for the angles 0, 30°, 45°, 60°, and 90° may be easily remembered if one notices the way the following table is built up.

Values of Trigonometric Functions

Angle	0	30°	45°	60°	90°	
Sin	$\frac{1}{2}\sqrt{0}$	$\frac{1}{2}\sqrt{1}$	$\frac{1}{2}\sqrt{2}$	$\frac{1}{2}\sqrt{3}$	$\frac{1}{2}\sqrt{4}$	
Cos	$\frac{1}{2}\sqrt{4}$	$\frac{1}{2}\sqrt{3}$	$\frac{1}{2}\sqrt{2}$	$\frac{1}{2}\sqrt{1}$	$\frac{1}{2}\sqrt{0}$	
Tan	0	$\sqrt{\frac{1}{3}}$	1	$\sqrt{3}$	∞	(Infinity)

The value of the tangent is obtained by dividing the sine by the cosine.

It is not worth while trying to memorize the values of the trigonometric functions for a large number of angles, but the ones given in the table are so easy to remember and so useful, that they should be committed to memory.

A Problem in Airplane Climb

Watching a very fast airplane climb, people will say that it is going almost straight up like a helicopter. As a matter of fact there is an optical illusion involved, and planes never climb at a very stiff angle.

Example: A fast army plane climbs 1,500 feet per minute while moving at 90 miles per hour along its flight path. What is its angle of the climb to the horizontal?

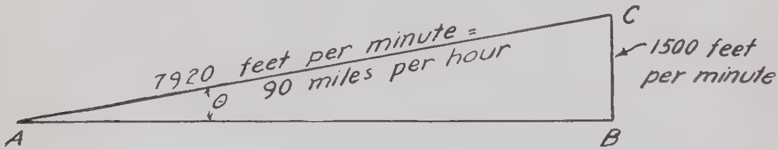


FIGURE 3

Sixty miles per hour is 1 mile per minute or 5,280 feet per minute.

$$90 \text{ miles per hour} = \frac{90}{60} \times 5{,}280 = 7{,}920 \text{ ft. per min.}$$

In Fig. 3 we want to find θ

$$\text{We know that } \sin\theta = \frac{BC}{AC} = \frac{1,500}{7,920} = 0.189$$

Looking in the trigonometric tables we will find that the angle whose sine is 0.189 is 10.9 degrees. This is much less than one would expect from an observation of the climb.

In Aeronautics, speed is expressed in both miles per hour and feet per second, so it is well to remember the following figures:

Sixty miles per hour corresponds to 88 feet per second.

One mile per hour corresponds to 1.467 feet per second.

Representing Velocity Graphically

It is very convenient in many problems to represent velocity graphically, both in direction and magnitude. Thus if a plane is going 60 miles an hour in a Northeast direction, the motion may be represented by the arrow marked A in Fig. 4. With

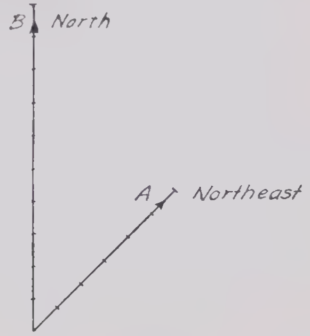


FIGURE 4

10 miles to the unit of length, 6 units will have to be marked off on this arrow.

Going North at 100 miles per hour, the motion may be represented by the arrow marked B, with 10 units marked off.

Relative Velocity and Composition of Velocities

Suppose a train is traveling at 60 miles an hour, and a man in it walks at 2 miles an hour in the train, in the same direction as the train is moving. Then his speed relative to the earth is 62 miles an hour. If he walks at 2 miles an hour in the opposite direction, then his speed relative to the earth is 58 miles an hour.

Similarly a plane traveling 100 miles an hour relative to the air in a tail wind of 20 miles, will travel relative to the earth at 120 miles an hour. If it is in a head wind of 20 miles, its speed relative to the earth will only be 80 miles an hour.

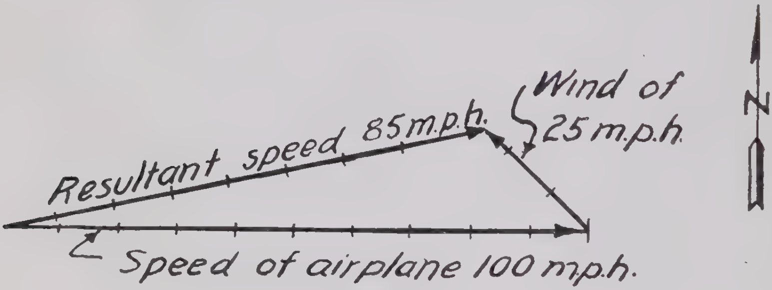


FIGURE 5

Where the direction in which the airplane is headed, and the direction of the wind do not coincide, it may be convenient to compound velocities graphically. Thus in Fig. 5, a plane traveling due East at 100 miles an hour, in a wind blowing from the Southeast at 25 miles, has a resultant velocity, or velocity relative to the earth of 85 miles per hour, as obtained graphically.

The same result could be obtained trigonometrically but with a little more trouble.

Forces, Their Resultant and Components

The idea of a force is so familiar to us that it needs no particular definition. Force is merely a push or a pull. Forces

may be represented and compounded graphically by the same method we used with velocities.

Thus in Fig. 6, we have an airplane wing with two forces acting on it; one a lift of 2,000 pounds; the other a drag of 200 pounds. The resultant is obtained graphically as shown, and its value is 2,010 pounds.

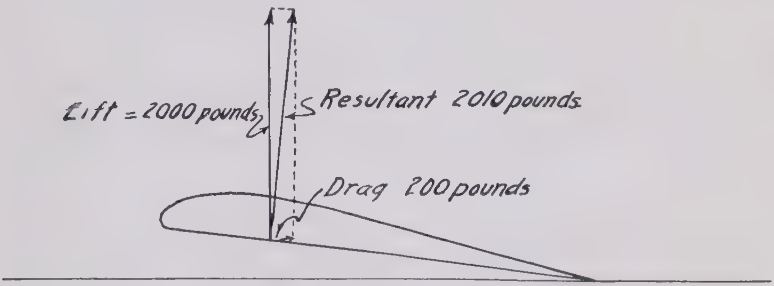


FIGURE 6

It is very useful sometimes to split up a single force into component parts. Thus if the resultant of Fig. 6 had been known in direction and magnitude to start with, we could have found the lift and drag components graphically.

Sometimes it is more convenient to find the components of a force by trigonometry. This can be illustrated by the case shown in Fig. 7, where a weight of 10 pounds is at rest on a rough inclined plane which is at 30° to the horizontal. The weight can be resolved into two components. One parallel to the plane, and the other at right angles to the plane. The force parallel to the plane will bear the same ratio to the weight as BC in the triangle will bear to AB.

$$\frac{F}{W} = \frac{BC}{AB} = \sin 30^\circ$$

so that $F = W \sin 30 = 10 \times 0.5 = 5$ pounds.

$$\text{Similarly } \frac{P}{W} = \frac{AC}{AB} = \cos 30°$$

$$\text{so that } P = W \cos 30° = \frac{10 \times \sqrt{3}}{2} = 5\sqrt{3} \text{ pounds.}$$

$$\text{Also } \frac{F}{P} = \frac{BC}{AC} = \tan 30° = \frac{1}{\sqrt{3}}.$$

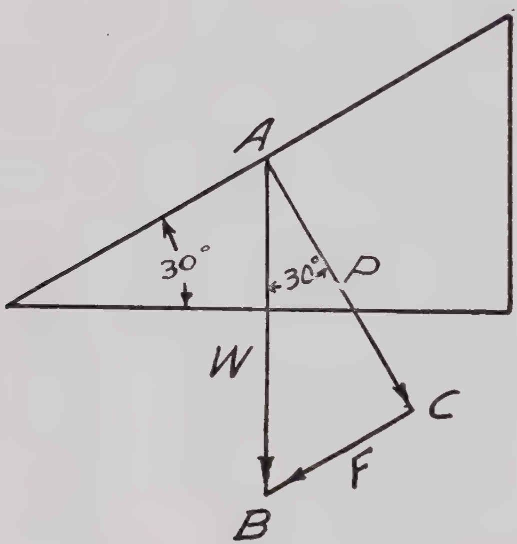


FIGURE 7

This method of splitting up a force will be very useful when dealing with problems in gliding or diving.

Center of Gravity: Moments

Gravity acts vertically downwards on every particle of a body, but every body has a point through which the resultant of these forces acts, and this point is termed the center of gravity. If a bar is supported on a hinge at its center of

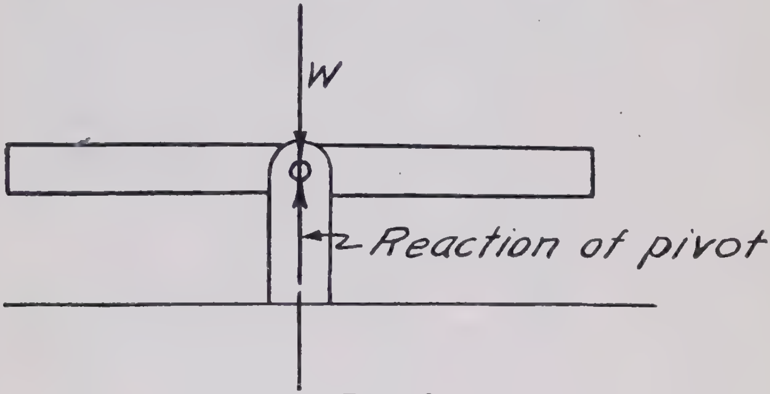


FIGURE 8

gravity as shown in Fig. 8, it will balance, because the resultant of the gravitational forces passes through the pivot. In other

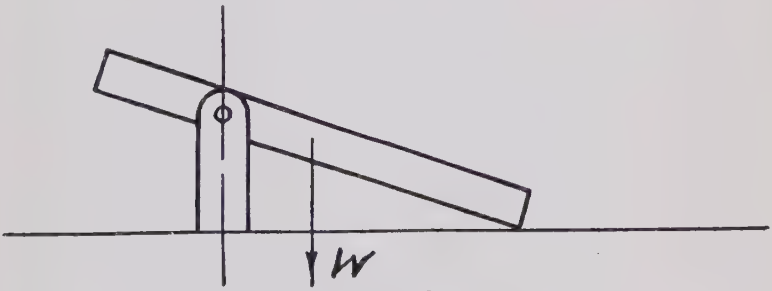


FIGURE 9

words the center of gravity of a body is the point about which the body will balance no matter what the attitude may be in which the body is placed.

If the bar were hinged at any other point than its center of gravity, it would not balance. This is illustrated in Fig. 9, where the bar will always tilt down on the right side till its tip touches the ground. This is because the resultant force of gravity does not pass through the pivot. It is said to have a moment about the pivot.

The moment of a force about a point is defined as the product of the force multiplied by its perpendicular distance from that point. In Fig. 10 a beam is built into a wall, the beam is 10 feet long, and a weight of 100 pounds is hung at its end. The

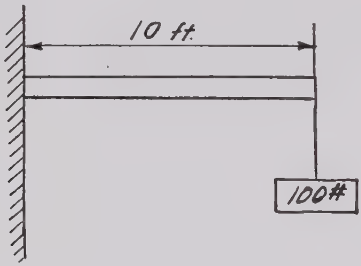


FIGURE 10

moment of the weight about the point 0 will be $100 \times 10 =$ 1,000 foot pounds.

An airplane, of course, has a center of gravity. It will only move steadily forward without changing the inclination of its wing, if the resultant of the air forces passes through the center of gravity.

Thus in Fig. 11 the lift force of 2,000 pounds passes through the center of gravity, and so has no moment about the center of gravity, the distance or arm being zero. But if the attitude of the wing is such that the lift force is ahead or behind the center of gravity, then the moment equilibrium is broken, and a force has to be applied at the tail. Thus if the lift force of Fig. 12 is 1.5 feet behind the center of gravity, there is a moment tending to nose dive the airplane, of $2{,}000 \times 1.5$, or 3,000 foot pounds. If the tail post of the airplane is 15 feet

behind the center of gravity, the elevator will have to be raised, so that there is a downward force on the elevator. Let this

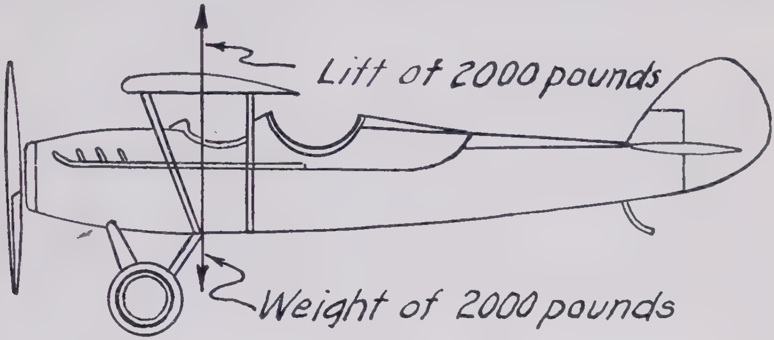


FIGURE 11

force be F. Then we shall have equilibrium, as far as moments are concerned, where

$$F \times 15 = 3{,}000, \text{ or } F = 200 \text{ pounds.}$$

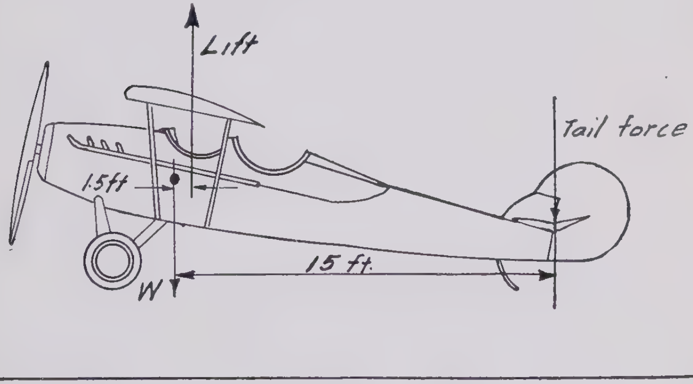


FIGURE 12

We now have an upward lift of 2,000 pounds and a down tail load of 200 pounds so the net lift is 1,800 pounds. If the

airplane and its contents weigh more than 1,800 pounds it will lose altitude and if less than 1,800 pounds it will gain altitude under these conditions. These ideas will be developed more fully in a later article on longitudinal stability.

Force and Acceleration

While the idea of force is so familiar, it is nevertheless capable of definition in terms of acceleration.

When a body falls through the air, and is so heavy and compact that it meets with scarcely any retarding influence from the air, it gains a speed of 32.2 feet per second when it has fallen 1 second, a speed of 64.4 feet per second when it has fallen 2 seconds, a speed of 96.6 feet per second when it has fallen 3 seconds and so on. It is said to have an acceleration of 32.2 feet per second per second. This is often denoted by the symbol g, to indicate that this is acceleration due to gravity.

A force which acts on a weight of 1 pound, and gives it an acceleration of 32.2 feet per second per second is said to be a force of 1 pound.

To give an acceleration of 1 foot per second per second to a weight of 1 pound, we shall need only a force of

$$\frac{1}{32.2} \text{ or } \frac{1}{g} \text{ pounds.}$$

So we get the equation $F = \frac{W}{32.2} \times a$

where

F = force in pounds
W = weight in pounds
a = acceleration in feet per second per second.

Work and Power

If a man raises a 100 pound weight 5 feet off the ground, he does 500 foot pounds of work. More scientifically expressed, work = force $\times$ distance.

The propeller does work in pulling the airplane through the air.

The engine does work in turning the propeller through the air.

Power is not the same thing as work. It is the rate at which work is being done.

When Watt invented the steam engine in the latter half of the eighteenth century, he coined the term horse-power and decided that a horse could do 550 foot pounds of work per second, or 33,000 foot pounds per minute. The definition has been in use ever since.

A problem or two will clarify the meaning of these terms.

Suppose an airplane is pulled by a propeller whose thrust is 500 pounds for a distance of 100 miles in one hour. What will be the work done by the propeller on the airplane and what will be the horse-power delivered by the propeller?

Since there are 5,280 feet in a mile, and work = force $\times$ distance, the work done $= 500 \times 100 \times 5{,}280 = 264{,}000{,}000$ foot pounds. This is done in one hour. Therefore the work per second $= \dfrac{264{,}000{,}000}{1 \times 60 \times 60} = 73{,}333$ foot pounds per second, and since 550 foot pounds per second is one horse-power, the horse-power is $\dfrac{73{,}000}{550} = 133.3$ horsepower.

Energy

As used in mechanics the terms work and energy are very closely related. Energy is often defined as "the ability to do work."

If a force of ten pounds is exerted while lifting a body vertically for a distance of 15 feet off the ground the work done upon the body is $10 \times 15 = 150$ foot pounds. (Force $\times$ distance.) The body now has potential energy of 150 foot pounds relative to the ground because on account of its elevated posi-

tion it has the ability to do 150 foot pounds of work in going from the elevated position back to the ground.

If the elevated body falls, it will of course lose potential energy because the force of gravity acting is always the same and the distance through which it can act is constantly becoming less as the body nears the ground.

Energy cannot be created or destroyed and in this case the potential energy which is being given up is being transformed into energy of motion or kinetic energy.

The kinetic energy of a moving body is given by the formula

$$E = \frac{WV^2}{2g}$$

where E = kinetic energy of the body in foot pounds,
W = weight of the body in pounds,
V = velocity with which the body is moving in feet per second,
$g = 32.2$.

An airplane weighing 2,400 pounds has a forward velocity of 45 miles per hour on landing. What is its kinetic energy upon landing and what retarding force must be applied to stop the airplane in 300 feet?

$$45 \text{ miles per hour} = \frac{45}{60} \times 88 = 66 \text{ ft./sec.}$$

$$E = \frac{2{,}400 \times (66)^2}{2 \times 32.2} = 162{,}000 \text{ ft. lbs.}$$

Work of stopping = force × distance must equal the kinetic energy.

Average force = 162,000/300 = 540 pounds.

Problems

1. A pilot wants to fly to a field due north at a distance of 200 miles. His air speed is 90 miles per hour and there is a wind from the east of 20 miles per hour. In what direction should he point his airplane to fly the shortest course? How far does he fly relative to the ground? How far does he fly relative to the air?

2. An airplane climbs 1,200 ft. per minute with an air speed of 80 miles per hour. What is the angle of climb to the horizontal if there is no wind? What is the angle of climb to the horizontal if there is a head wind of 15 miles per hour?

3. What must be the value and direction of the tail force on an airplane for horizontal flight with the resultant lift force 3,000 pounds, ½ foot behind the center of gravity, when the distance from the center of gravity to the tailpost is 20 feet?

4. A 4,000 pound airplane lands at 50 miles per hour on a hard dry field. What will be the length of the landing run if the retarding force averages 800 pounds?

Answers to Problems

(1) North 12½° East, 200 miles, 206 miles.
(2) 9.9°, 12.1°.
(3) 75 pounds down.
(4) 415 feet.

CHAPTER II

PROPERTIES OF THE AIR AND ATMOSPHERE

Nothing is really simpler than the aerodynamics which the pilot or even the designer of airplanes needs to know. But to study even simple aerodynamics with benefit, it is essential to have a grasp of a few underlying physical principles, which we propose to develop in this chapter and the next.

Properties of Air

The air surrounding the earth and constituting the atmosphere extends to an immense height, perhaps 200 miles above the earth's surface. At great heights it is exceedingly rare and light, and probably completely devoid of living organisms. (Some of us may remember, however, Conan Doyle's weird story of tenuous beings, existing many thousands of feet above the ground, who, with clutching tentacles, caused the doom of adventurous aviators.) Even at ground level, air is a very light gas. But the height of the air is so great that it exercises a heavy pressure at sea level. Luckily for us the pressure on our bodies is both external and internal, and its effects are not felt, otherwise we would collapse.

Standard Air

The high speed and landing speed of our airplanes are reported as having been found at ground level. But both the pressure and temperature of the air, and therefore its density, or weight per cubic foot, at ground level change from day to day, and changes in density affect the power of the engine and the performance of the plane. The greater the density the better the performance. The sales manager of an airplane factory with a knowledge of physics and aerodynamics might see

to it that speed tests were made on a cold day when the barometer stood very high. His announcement of tests in Aeronautics magazines would then show a decided superiority over the tests of other manufacturers not so well versed in scientific matters.

Unfortunately, the wily sales manager is defeated by the definition of "Standard Air" at sea level, which fixes once and for all the conditions to which a test should be referred. Standard air represents roughly average conditions in the temperate zone, of which the United States is a part, and is defined as: Air at 59° Fahrenheit and barometric pressure at 29.92 inches of mercury. This corresponds to a pressure of 2,117 pounds per square foot (or 14.7 pounds per square inch) which bears out our contention that the air exercises a tremendous pressure.

Standard Atmosphere

As we rise above the earth's surface, the temperature diminishes at the rate of approximately 1° Fahrenheit for every 300 feet, and the pressure drops also. So of course does the density.

The "standard atmosphere" at different altitudes is used for comparing climb tests of planes. This is merely an arbitrary definition of conditions of temperature, pressure, and density at altitudes other than sea level. Just as "standard air at sea level" is an arbitrary standard for comparison of high speed and landing speed so "standard atmosphere" is a standard for comparison of climb tests.

In Figure 13, we have plotted curves of temperature and pressure against altitude, and also the relative density or density at a given altitude as a percentage of the density at ground level.

The exact manner in which the horse-power of an engine falls off with altitude is a complex question. The loss in power depends mainly on the density; the less the density the less the weight of air drawn in on the suction stroke. But the power loss depends on the pressure and temperature also. In conditions of standard atmosphere, the percent of the sea-level

power which is obtained at altitude may be fairly well represented by the curve of Figure 14. Loss of power at altitude will be discussed more fully later, but this curve is not out of place at this point.

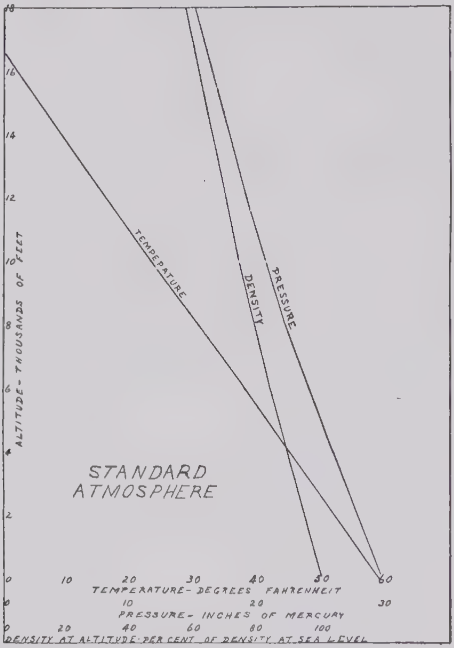


FIGURE 13

Calculating Density from Pressure and Temperature

In performance tests of any kind, we have no way of directly determining density. In the physics or chemistry laboratory, it is comparatively easy to exhaust a vessel of known volume of its air, and to determine the density by weighing. This would be quite impossible on the flying field.

Two laws of physics fortunately give us a method of figuring

density once the pressure is known from the altimeter or the barometer, and the temperature from the thermometer.

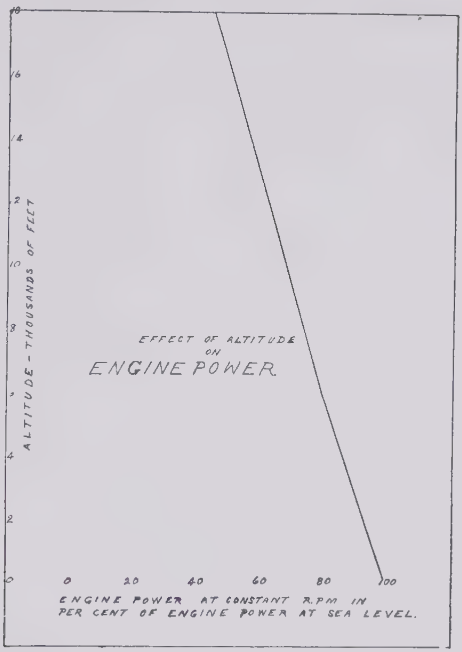


FIGURE 14

Boyle's Law is the first of these. Suppose we have a mass of gas in the cylinder of an engine, which is so slowly compressed by the piston that the temperature remains constant. If the piston moves so much that the volume is halved, the pressure will be doubled. Conversely if the volume is doubled, the pressure will be halved. In other words, if the temperature remains constant, the pressure and volume of a given weight of gas will vary inversely as one another.

The second law is Charles' Law. This states that when a gas is kept at constant pressure, the volume of a given mass

varies proportionately to the absolute temperature. The absolute zero of temperature is the point at which all heat energy disappears (a condition only to be found in interstellar space) and is 459.4 degrees Fahrenheit below 0° Fahrenheit. Gay-Lussac's Law is a combination of the two.

We will find it useful to modify these laws so as to bring in the density. At constant temperature, when the pressure increases, the volume diminishes. Hence density increases with increased pressure.

At constant pressure, when the temperature increases, the volume increases. Hence density diminishes with increased temperature.

Given these laws the density of air can be readily calculated if the pressure and temperature are known. These laws and ideas will also be found useful in the consideration of the engine power and are therefore doubly useful.

The Value of Illustrative Examples

Our reader will find nothing so valuable in bringing home principles, as studying the simple problems that follow.

Shall We Get Good High Speed Today?

This is quite a practical question to ask. The few principles of physics dealt with, will enable us to answer this question readily. If the pressure is high, and the temperature is low, we shall certainly have high density and a good test.

Suppose, however, that the pressure is high, say 30 inches on the barometer, and the temperature is high also, say 80° Fahrenheit. The Absolute temperature is $80 + 459.4 = 539.4°$. Standard air, at 29.92 inches pressure, and 59° Fahrenheit or 518.4° Absolute, has a density of .0764 pounds per cubic foot.

If the pressure rises to 30.00 inches, then by our modification of Boyle's Law, the density will increase in proportion to the pressure:

$$.0764 \times \frac{30.00}{29.92} = .0766$$

But since the temperature has risen, the density will decrease proportionately. Thus the density will be:

$$.0766 \times \frac{518.4}{539.4} = .0753 \text{ pounds per cubic foot.}$$

The combined effect of pressure rise and temperature rise will be therefore to lower the density, and therefore to decrease engine power and the high speed.

Loss of Engine Power at Altitude

One of the principal causes of the loss of engine power at high altitudes is that the cylinders do not receive as heavy a charge as they do at the ground.

The volume of a cylinder 3 inches in diameter, and 5 inches long is:

$$\frac{\pi \times 3 \times 3}{4} \times 5 = 35.3 \text{ cubic inches or } 0.0204 \text{ cubic feet.}$$

On the suction stroke of the piston the cylinder is filled with the charge.

With standard air at sea level a cubic foot of air weighs 0.07641 pounds so the charge in this case is $0.0204 \times 0.07641 = 0.001565$ pounds.

At 14,000 feet the standard temperature is 9.1° Fahrenheit or $9.1 + 459.4 = 468.5°$ Absolute.

At sea level the temperature is 59° Fahrenheit or $59 + 459.4 = 518.4°$ Absolute.

The density of the air corrected for the change in temperature only is then:

$$0.07641 \times \frac{518.4}{468.5} = .08415 \text{ pounds per cubic foot (Charles' Law).}$$

At 14,000 feet the standard pressure is 17.50 inches of mercury. By use of Boyle's Law we find that the density cor-

rected for both change in temperature and change in pressure is:

$$\frac{17.50}{29.92} \times 0.08415 = 0.0426 \text{ pounds per cubic foot.}$$

The weight of charge take in at 14,000 feet is then $0.0204 \times 0.0426 = 0.00087$.

Since this value is only about ½ of that for sea level conditions we cannot expect the engine to develop its full power. It will develop even less than ½ of its sea level power because the friction losses remain the same while the power developed diminishes.

How High is Denver?

A pilot intending to land or take off at Denver or at any other locality of high altitude, will do well to find out what this elevation is, for the density changes with altitude, and density affects his landing and his get-away. The following problem will help illustrate this case. Suppose the pressure in some locality was 25 inches of mercury, and the temperature was 59° Fahrenheit. What is its elevation?

25 divided by 29.92 will give us the part of standard pressure or, in this case, about .835 which is 83½ percent. Since density is proportional to pressure, find 83½ on Figure 13 (read along line Density at altitude—percent of density at sea level). The altitude corresponding to this density gives us 4,800 feet.

Problems

1. What will be the density of air at a pressure of 22.50 inches of mercury and at a temperature of 10° Fahrenheit? (Use Boyle's Law and Gay Lussac's Law.) Ans. 0.0635.

2. What is the density of standard atmosphere at 10,000 feet? (Use curves of Figure 13.) Ans. .0561.

3. An engine develops 225 horse-power at 1,800 r.p.m. at sea level. What power will it develop at 1,800 r.p.m. at 8,000 feet elevation? (Use curve of Figure 14.) Ans. 163+.

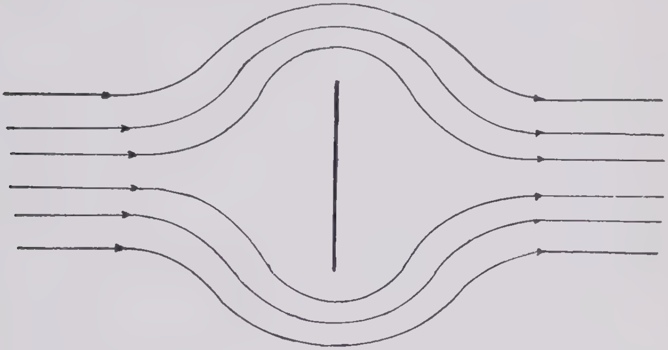
CHAPTER III

STREAMLINE FLOW—BERNOUILLI'S LAW

Perfect Fluid and Streamline Flow

A perfect fluid is one in which there is no loss due to friction. Of course no fluid like air or water is frictionless. Streamline flow may be defined as flow in which all changes of direction are gradual, and in which no eddies or whirls are formed. Streamline bodies may be defined as bodies whose section changes gradually and round which the flow is without eddies or whirls.

In a perfect fluid all bodies would be streamline. For example the flow round a flat plate like that shown in Figure 15,



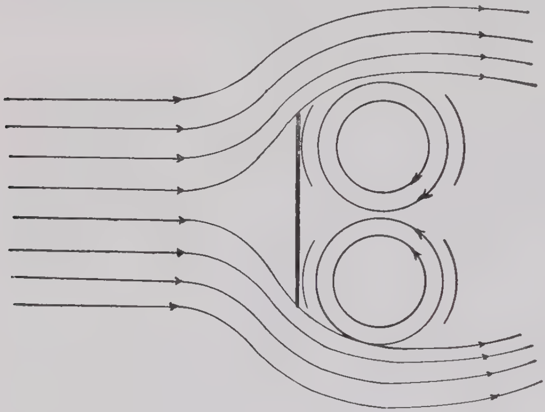
FLOW AROUND A FLAT PLATE IN A PERFECT FLUID

FIGURE 15

would be streamline, and perfectly symmetrical in front of and behind the plate. As a matter of fact the actual flow round

a flat plate is like that shown in Figure 16, with large eddies behind the plate.

Even a fish-like or streamline body like that shown in Figure



ACTUAL FLOW AROUND A FLAT PLATE
FIGURE 16

17, disturbs the flow slightly, not at the bow or front end, but at the tail, where small eddies cannot be avoided. For a very well streamlined body, these eddies are so small however that the flow is very like that which we would find in a perfect, frictionless fluid.

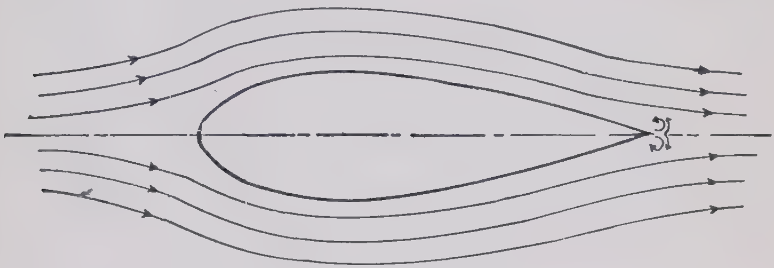
Therefore, while a perfect fluid does not exist in nature, we can assume a perfect fluid in theorizing about streamline bodies, and the conception of a perfect fluid is very useful to the aeronautical engineer.

Of course in practical airplane design, the idea of a perfect fluid is disregarded, and the engineer tries to make all objects exposed to the wind as streamlined as possible.

Bernouilli's Law

It is surprising how many famous Italian names appear in aeronautics.

Thus Leonardo da Vinci, the versatile and immortal genius of the fifteenth century, made the first scientific observations on the theory of flight.



FLOW AROUND AROUND A FISH-LIKE OR STREAMLINE BODY

FIGURE 17

Another Italian discovered the Venturi tube, so frequently used in the measurement of air and water flow.

Bellanca's monoplane designs need no introduction to our readers.

Still another Italian, Bernouilli, enunciated the famous law, known by his name, which connects pressure and velocity for a fluid in motion.

This law states that if a fluid is perfect or frictionless, then the energy of a part of the fluid along a streamline always remains the same.

This law is true, to a very close approximation for such flow as we encounter in aerodynamics.

The energy of a fluid may be divided into three parts:

1. That due to position or height, which is termed potential energy.

2. The pressure energy.

3. The energy due to motion or kinetic energy.

It is most important to be able to express these components of energy all in the same way.

It is easier to do this by first thinking of water (which has a density of 62.5 pounds per cubic foot).

Suppose we have a tank, 1 square foot in area, as shown in Figure 18, open to the atmosphere, with a column of water 10 feet high, what is the pressure per square foot at the bottom

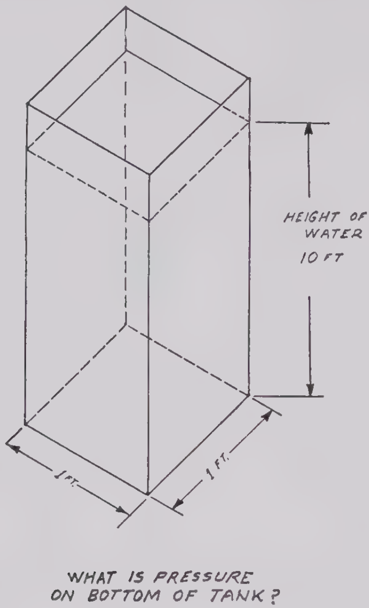


FIGURE 18

of the tank? The pressure per square foot at the bottom of the tank will be that due to the atmospheric pressure plus the pressure of the weight of water, that is $2117 + 10 \times 62.5 = 2742$ pounds.

In other words to convert head of water in feet into pressure per square foot in pounds, we must multiply the density by the head.

If as in Figure 19, the tank is opened through an orifice, to the air, the water will come out of the tank with a certain velocity v (in feet per second) and its kinetic energy per pound will be $\frac{v^2}{2g}$ (see Chapter 1).

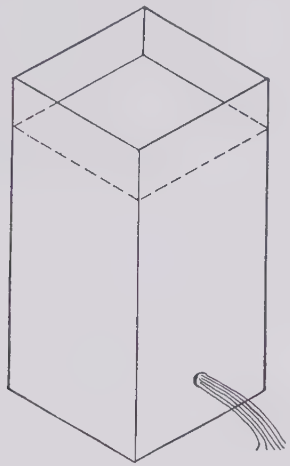


FIGURE 19

Now this kinetic energy is due to the drop h. Therefore

$$\frac{V^2}{2g} = h.$$

And since the pressure due to the head h is $w \times h$, the pressure equivalent of the kinetic energy is also $\frac{W\,V^2}{2g}$.

So that if we call the pressure in pounds per square foot, the total energy will be $p + \frac{w\,v^2}{2g} + wh$.

According to Bernouilli, this must remain a constant and so along a streamline.

$$p + \frac{w\,v^2}{2g} + wh = C \text{ where } C \text{ is a constant.}$$

Suppose instead of opening into an orifice the tank opened into a pipe, as in Figure 20, of varying cross-section, and we

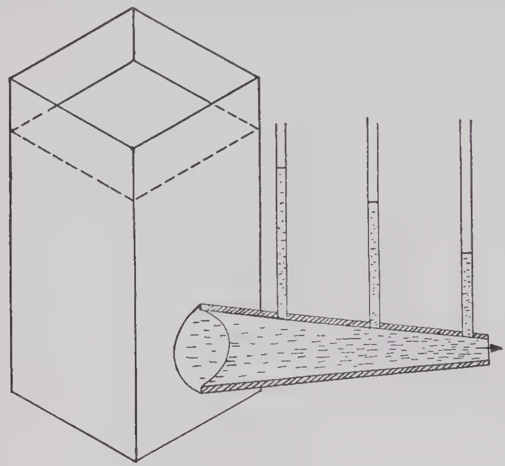


FIGURE 20

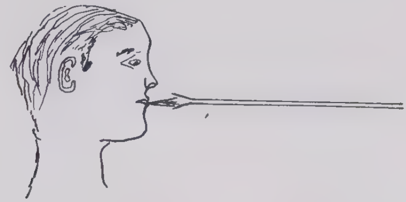
had tubes opening to the atmosphere, placed along this pipe.

At narrow sections of the pipe, the velocity and kinetic energy of the water are large, and the water rises but a little height in the tube. Where the pipe is large in cross-section, the velocity and the kinetic energy are small, and the water rises almost to the same level as in the tank.

In aerodynamics we are not concerned with position head or potential energy, because we are primarily interested in flow, at one level, so that Benouilli's equation becomes simply

$$p + \frac{w\,v^2}{2_g} = C, \text{ with } w \text{ the weight of one cubic foot of air.}$$

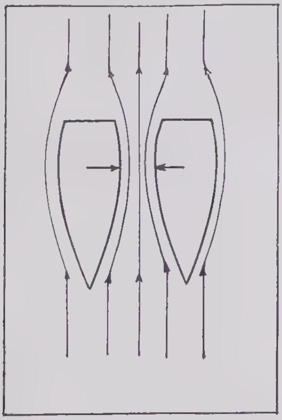
We can say that in aerodynamics the pressure, plus the pressure equivalent of the velocity remain constant. Where the pressure is high, the velocity is low and vice-versa.



MAN BLOWING - TRYING TO SEPARATE TWO SHEETS OF PAPER
FIGURE 21

Some Curiosities Explained by Bernouilli

Suppose that a man blows between two sheets of paper (cigarette paper for preference), as shown in Figure 21. They will not blow apart, but stick the more closely, the harder he

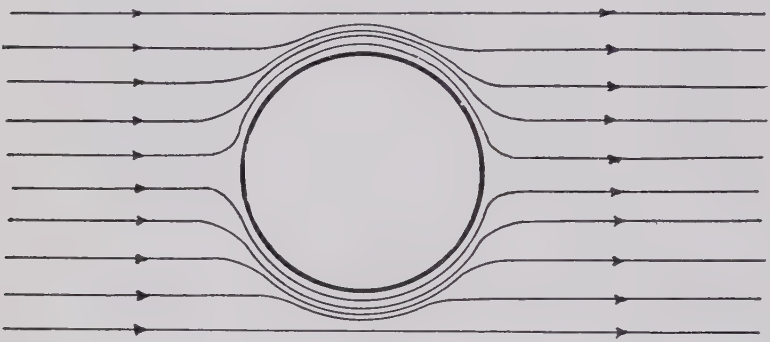


TWO BOATS MOORED CLOSE TOGETHER IN A STREAM DRAW TOGETHER

FIGURE 22

blows. That is because the moving air loses pressure in accordance with Bernouilli.

Two boats moored close to one another in a stream as shown in Figure 22, are drawn together. Why is that? Because the water flow between them is more rapid than the flow on their outersides. Therefore the pressure on their inner sides is less than the pressure on their outer sides.



FLOW AROUND A STATIONARY CYLINDER

FIGURE 23

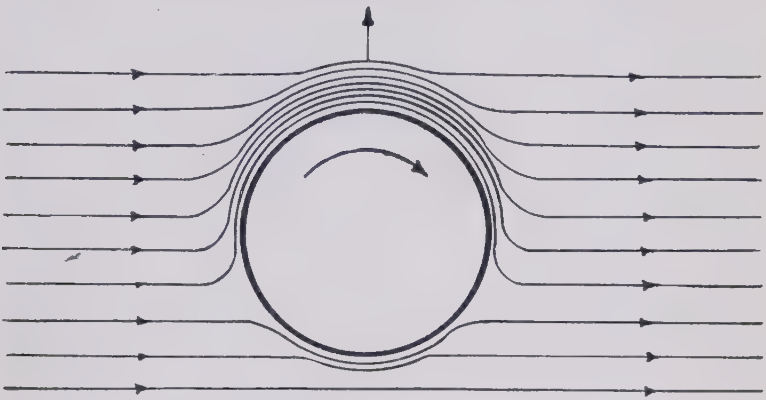
The action of Flettner's famous rotor ship is explainable by Bernouilli. Figure 23 shows the flow round a stationary cylinder (neglecting friction effects). When the cylinder is rotated as shown in Figure 24, it will crowd the streamlines above the cylinder, and the velocity will be greater above than below the cylinder. Hence by Bernouilli, the pressure below will be greater than the pressure above, and the cylinder will experience an upward force as shown in our diagram.

Bernouilli's principle will also explain how a pitcher throws an "up" curve. The flight of a golf ball may also be studied in the same manner.

Many Applications of Bernouilli in Aerodynamics

The reader may question the value of the preceding paragraphs. They were intended to give him a fundamental under-

standing of the great law, which we will now apply to some aerodynamical problems:



FLOW AROUND A ROTATING CYLINDER
FIGURE 24

The Air in Flying May Be Considered Incompressible

An airship is moving through the air at 100 feet per second in air having a pressure of 2117 pounds per square foot. What is the excess in pressure at the center of the bow of the airship? At this point the relative air velocity is reduced to zero. All the relative kinetic energy is converted into pressure. The equivalent of the kinetic energy pressure is

$$\frac{w\,v^2}{2g} \text{ or } \frac{.0764 \times 100^2}{2 \times 32.18} = 11.9 \text{ pounds per square foot.}$$

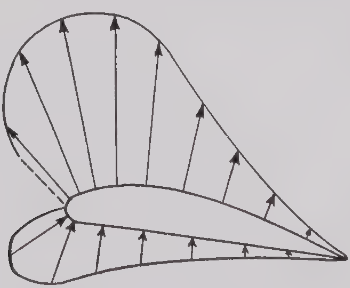
This is not very much as a percentage of the undisturbed air pressure of 2117 pounds. The air as we encounter in aviation may be considered as incompressible. It is only at the tips of fast moving propeller blades, or when we attain velocities of 500 miles per hour, that the compressibility of the air will begin to bother us.

Explaining the Lift of the Wing

If the man in the street is asked what the lift of the airplane's wing is due to, he is likely to say that it is due to the pressure of the air on the under surface of the wing. But if as in Figure 25 we draw the lines of flow round a wing, we

FLOW AROUND A WING
FIGURE 25

see that the air underneath experiences scarcely any change in velocity. The air above the wing has to undergo an increase in velocity, because it is going round a curve. Therefore,



PRESSURE DISTRIBUTION AROUND A WING
FIGURE 26

again from Bernouilli's law there will be a decrease in the pressure above the wing; or a suction if we like to call it so.

It is this suction which is mainly responsible for the lift on the wing. There may be some excess pressure underneath, but this will not be nearly as great as the suction above. Figure 26 shows a typical distribution of the pressure round a wing. We shall later have to discuss pressure distributions for a wing in greater detail.

CHAPTER IV

ELEMENTARY PRINCIPLES OF FLIGHT

Elementary Principles of Flight

There is a certain similarity between airplane flight and swimming. If a man in deep water remains motionless he will sink. When swimming, the reaction of the water against his moving body will support him. To attain movement through the water he must exert muscular energy, propelling himself by the use of arms and legs against the resistance of the water. In the airplane, the wings or supporting surfaces meet the rush of air and experience a lift which sustains the plane against the action of gravity. The thrust or pull of the propeller, actuated by the power of the engine, overcomes the drag or resistance of the plane to forward motion.

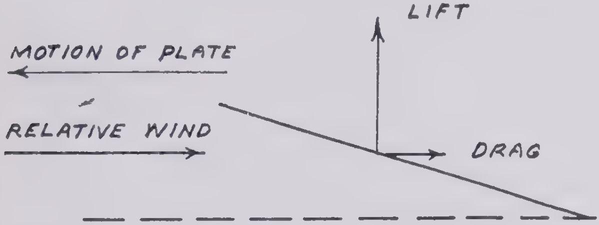
Figure 27 illustrates the movement of a flat plate through the air when inclined at a small angle to the direction of motion. A lift force at right angles to the motion and a drag or resistance force parallel and opposite to the direction of motion are experienced.

Principle of Relative Motion

A stationary object with air moving by at a certain speed will have the identical forces acting on it as an object moving through the air at that speed. This may be termed the Principle of Relative Motion. The "relative wind" then determines the amount and direction of the air forces. In flight the speed of a plane relative to the air may be greater or less than its speed relative to the ground. When flying against the wind its air speed is greater than its ground speed and vice versa.

Variation of Resistance of a Flat Plate Normal to the Wind with Density, Area and Velocity

In rowing a boat, when the oar is submerged we must exert a great deal of energy to move the oar against the resistance of the water. When the oar is raised above the water for the return stroke very little effort is required to move it back



LIFT AND DRAG OF A FLAT PLATE INCLINED TO ITS DIRECTION OF MOTION

FIGURE 27

through the air. This indicates that the resistance offered to the movement of a surface depends upon the density of the medium through which it is moving. We may say that the more dense a fluid the greater is the resistance it offered to motion.

A flat plate of one square foot area held perpendicular to the relative wind will offer a certain amount of resistance to motion; a plate of twice the area will obviously offer twice the resistance and so on. Thus the resistance varies proportionately to the area.

In driving an automobile at 30 m.p.h. we hardly notice any air resistance. At 60 m.p.h. there is an appreciable retarding air force and the wind howls in our ears. We can feel that this force is not merely twice that at 30 m.p.h. but much greater. In moving at 60 m.p.h. we are not only hitting twice as much air in a given time but we are hitting each particle

just twice as hard as at 30 m.p.h. Thus we can see the resistance effect of the air will vary as the square of the velocity. The air resistance at 60 m.p.h. then is four times that at 30 m.p.h.

We have now established the fact that *the drag or resistance of an object varies proportionately to the density of the medium in which it is moving, the area of the object, and the square of the velocity.*

Weight, Mass, Specific Weight and Density.

If an object has a weight of one pound, it is acted upon by gravity with a force of one pound.

The force of gravity varies somewhat with the distance from the equator, and with the height above the earth's surface.

The force of gravity, g, is defined by international standards by saying that a force of one pound acting on a weight of one pound produces an acceleration of 32.174 feet per second per second, (written ft./sec.^{2}).

While the weight of an object depends upon the value of gravity, the amount of matter or mass in an object is evidently independent of gravity.

In physics or aerodynamics it is very often useful to work in terms of mass rather than of weight. The mass of an object weighing one pound is said to be $\frac{1}{g} = \frac{1}{32.174}$ or $M = \frac{w}{g}$.

In Chapter 2, we stated that standard air, at 29.92 inches of mercury pressure and 59° Fahrenheit temperature had a density of .0764 pounds per cubic foot.

We would have done better to call this the specific weight. The density is really the mass per cubic foot. The mass or density per cubic foot of Standard Air will then be

$$\frac{.0764}{g} = \frac{.0764}{32.174} = .00238.$$

The density of air is generally denoted by the Greek letter ρ(rho). Mass is denoted by the symbol M.

Momentum, Acceleration and Force

Momentum is defined as the product of mass by velocity, $Mv = \frac{Wv}{g}$.

Example: What is the momentum of a weight of 10 pounds moving at a speed of 10 feet per second? The mass is $\frac{10}{g} = .31$. The momentum is $Mv = .31 \times 10 = 3.1$.

In Chapter I, we saw that $F = \frac{Wa}{g}$. Therefore $F = Ma$ or force equals mass times acceleration.

If a body of Mass M acquires a momentum Mv in one second, then the acceleration is also v and the force exercised will be proportional to Mv or the momentum acquired in one second.

Mathematical Proof of the Resistance Law

We can, with the aid of the above paragraphs give a mathematical proof of the resistance law.

Imagine a flat plate held normal to a stream of air. The amount of air striking the plate depends upon the density of the air, the area of the plate, and the velocity of the air. We can therefore write that the amount of or mass of air M is proportional to ρAv where

ρ = density
A = area
v = velocity.

The amount of momentum which the plate must take up per second is proportional to Mv. Thus the resistance or force experienced by the plate must be proportional to Mv, and since M is proportional to ρAv, R is proportional to $(\rho Av) \times v$ or ρAv^2.

Resistance of a Flat Plate Perpendicular to the Wind

The great Newton imagined the flow of a fluid to consist of the movement of a great number of individual particles. He thought that if a flat plate was held normal to an air stream, all the particles after striking the plate would fly off sideways with the forward velocity completely gone. Then the force on the plate would be given by the equation $R = \rho AV^2$. Experimentally, however, it has been proved that R does not equal ρAV^2 but is only proportional to it, because the air does not quite follow Newton's simplified conception of its behavior.

The American aeronautical engineer in the calculation of flat plate resistance employs the equation: $R = KAV^2$ where

K = Constant derived from experiment
A = Area in square feet
V = Velocity in M.P.H.

The value K is known as the Coefficient of Resistance. It has been found more convenient to include the density ρ(rho) directly in this constant. For the case of a large square flat plate held perpendicular to the wind the value of $K = .0032$ has been generally accepted as sufficiently correct.

Example: Find the resistance of a square flat plate 16 square feet in area held perpendicular in a 60 mile wind.

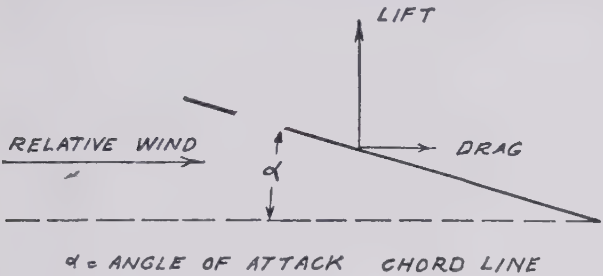
$$R = KAV^2$$
$$R = .0032 \times 16 \times (60)^2$$
$$= 184.32 \text{ pounds.}$$

General Law of Variation of Aerodynamic Forces

When a surface is inclined to the wind there is created a lift force as well as a drag or resistance on the surface. These forces are as shown in Figure 27. By analogous reasoning to that in a preceding paragraph it may be shown that the lift force on an inclined surface will follow the same law of variation with density, area, and velocity squared. In fact all aerodynamic forces follow a similar law. For each kind of force and every different surface the constant K will change but in each case is readily determined by experiment.

Angle of Attack

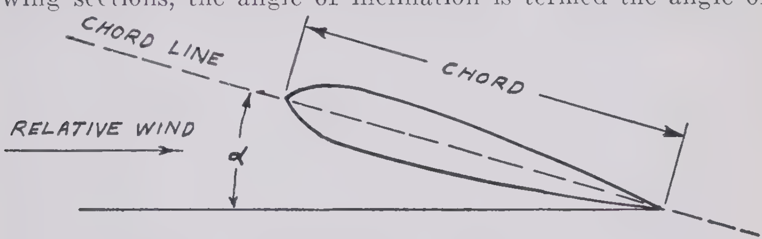
We have seen that two forces, Lift and Drag, are produced when a flat plate is moved inclined to its direction of motion, or to the relative wind. Since these two forces vary with each



CHORD AND ANGLE OF ATTACK FOR A FLAT PLATE
FIGURE 28

inclination, even if the speed is constant, it is important to define the angle of inclination for all surfaces.

For all surfaces, whether flat plates or curved (cambered) wing sections, the angle of inclination is termed the angle of

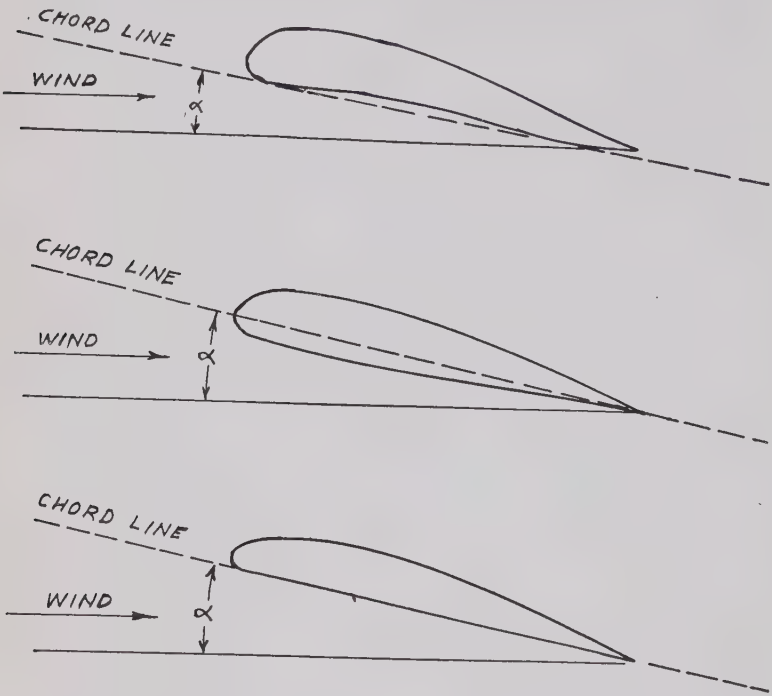


CHORD AND ANGLE OF ATTACK FOR DOUBLE-CAMBERED SURFACES
FIGURE 29

attack, and is defined as the acute angle d expressed in degrees, between the relative wind and a line in the section termed the chord.

In the case of the flat plate shown in Figure 28, this line

coincides with the surface of the plate. In a symmetrical, double-cambered section, as shown in Figure 29, the position of the chord is not in doubt. In a wing section, cambered sec-



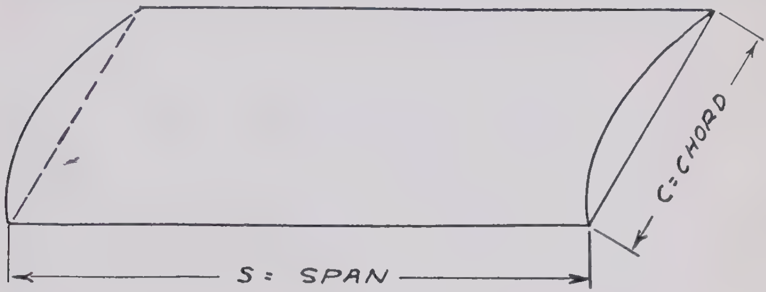
CHORD AND ANGLES OF ATTACK FOR VARIOUS AIRFOILS

FIGURE 30

tion, or airfoil as it is variously called, there is always doubt as to what is the chord line. It is generally fixed by the original designer of the section. Some representative examples are shown in Figure 30.

Span, Chord and Aspect Ratio

In Figure 31 the meaning of the terms Span and Chord as applied to an airfoil is illustrated. The chord length is the distance between the leading and trailing edges measured



SPAN AND CHORD OF A WING

FIGURE 31

along the chord line. The span is the width of the wing, or the length from tip to tip. It has been found that the aerodynamic properties of a wing depend not only upon the shape of its cambered section but also upon the ratio of span to chord. This ratio has been given the name of Aspect Ratio (AR).

Thus for a wing rectangular in form: $$(AR) = \frac{\text{Span}}{\text{Chord}} = \frac{S}{C}$$

Lift and Drag Coefficients

In Figure 27 was shown a flat plate inclined to the relative wind, with the force L, or lift, perpendicular to the wind, and the force D, or drag, along the line of the wind. These values of the lift and drag vary as the product of density, area and velocity squared as we have shown. The airflow varies for each angle of attack however so there must be different coefficients for each such angle. These coefficients also vary with

each different shape of wing section. We may write the equations for lift and drag as follows:

$$L = K_yAV^2 \text{ and } D = K_xAV^2$$

where

L = Lift in pounds
D = Drag in pounds
A = Area in square feet
V = Velocity in m.p.h.
K_y = Coefficient of lift for a given angle and section
K_x = Coefficient of drag for a given angle and section.

As in the formula for the resistance of a plate normal to the wind the density is included in the constant for convenience.

Example: Given a rectangular wing of 30 ft. span and 5 ft. chord with a coefficient of lift = .0028. Find the lift force at 50 m.p.h.

$$\text{Area} = 30 \times 5 = 150 \text{ sq. ft.}$$
$$L = K_yAV^2$$
$$L = .0028 \times 150 \times (50)^2 = 1050 \text{ lbs.}$$

The same wing has a drag coefficient of .00034 at the same angle of attack. Find the drag force at 50 m.p.h.

$$D = K_yAV^2$$
$$D = .00034 \times 150\ (50)^2 = 127.5 \text{ lbs.}$$

Lift Over Drag

The ratio of lift over drag, L/D, is evidently a measure of the efficiency of the wing. The value of L/D is also equal to the ratio of lift coefficient to drag coefficient $\frac{K_y}{K_x}$ for

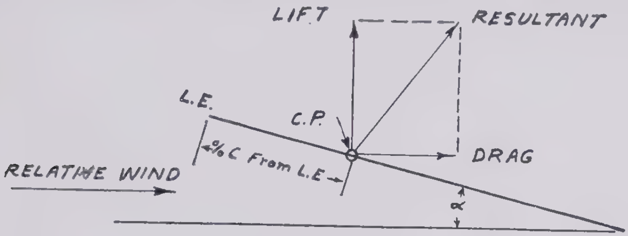
$$L/D = \frac{K_yAV^2}{K_xAV^2} = K_y/K_x$$

Resultant Force and Center of Pressure

The two forces, Lift and Drag, of Figure 27 may be combined into a single force known as the Resultant Force. This

has been done in Figure 32. It should be noted that the resultant force is not usually perpendicular to the chord.

The point of application of this force along the chord line is called the Center of Pressure (C. P.). The position of the



RESULTANT FORCE AND CENTER OF PRESSURE
FIGURE 32

C. P. is designated by its distance from the leading edge of the surface given as a percentage of the chord length. Thus if the chord length in Figure 32 be 60 inches and the resultant force act at 15 inches from the leading edge, its position would be given by 15/60 = 25% of the chord from the leading edge. Briefly it is said that the C. P. acts at 25% of the chord.

Problems

1. Define "Lift of an Airplane."
2. Define "Drag of an Airplane."
3. (a) How is the Resultant Force on a surface obtained? (b) What is the Center of Pressure?
4. A plane is flying at an air speed of 80 m.p.h against a 20 mile wind. What is the speed of the plane relative to the ground? What would be the speed relative to the ground if the plane was flying with the wind? Ans., 60 m.p.h., 100 m.p.h.
5. The coefficient of resistance of a square flat plate placed perpendicular to the wind is .0032 in Engineer's Units. What will be the resistance of a plate of 10 square feet in a wind of 100 m.p.h. Ans., 320 lbs.

6. A square flat plate normal to a wind of 120 m.p.h has a resistance of 210 pounds. Find the area of the plate. Ans., 4.5 sq. ft.

7. A rectangular wing has an area of 300 square feet and a span of 40 ft. Find the chord and aspect ratio. Ans., Chord 7.5 ft.; Aspect Ratio 5.3.

8. What is the lift force on the wing in Problem 7 in a wind of 80 m.p.h., if the K_y coefficient is .00132? Ans., 2,534 lbs.

9. Find the drag force under the same conditions as in Problem 8 if the value of K_x is .000198. Ans., 380 lbs.

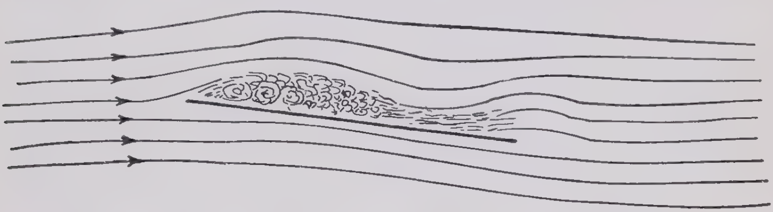
10. What is the L/D ratio of the wing in Problems 8 and 9? Check your answer by finding K_y/K_x. Ans., 6.66.

CHAPTER V

FLOW ROUND A WING—EXPERIMENTAL METHODS—A TYPICAL WING

Why a Cambered Surface Is Better Than a Flat Plate

Almost any surface inclined to the wind will provide lift, and a flat plate will provide lift. But besides securing lift from a wing, we need a high efficiency, that is a high ratio of lift to drag, and this is largely a question of smooth flow. In Figure 33, we show diagramatically the flow of air round a flat plate



FLOW OF AIR AROUND A FLAT PLATE

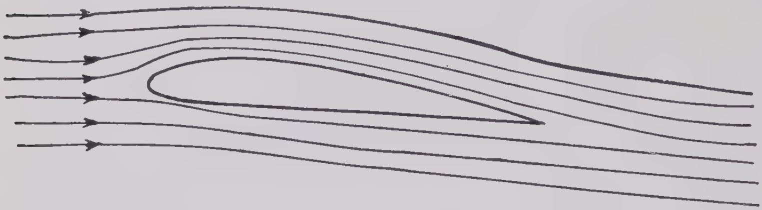
FIGURE 33

inclined at a small angle. In spite of the small inclination the flow is disturbed and there are eddies or whirls on the upper surface of the plate. For the cambered wing of Figure 34, the flow is perfectly smooth, though the wing is inclined at 2 degrees. This is a visual and convincing proof of the superiority of the cambered wing.

Flow Round a Wing Changes with Inclination

In Figure 35 the same wing is shown at an inclination of 10 degrees. The flow begins to be fairly turbulent. At 18 degrees

inclination as shown in Figure 36, the flow is very rough indeed, and the air does not follow the upper contour of the wing at all.

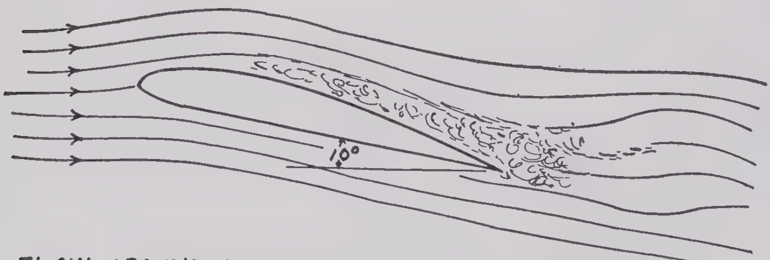


FLOW OF AIR AROUND A CAMBERED SURFACE INCLINED AT 2 DEGREES.

FIGURE 34

From these diagrams of the flow (which are based on actual photographic studies), the following conclusions can be drawn:

At small angles, the flow is smooth, the air is deviated but little. The drag as well as the lift will be small.

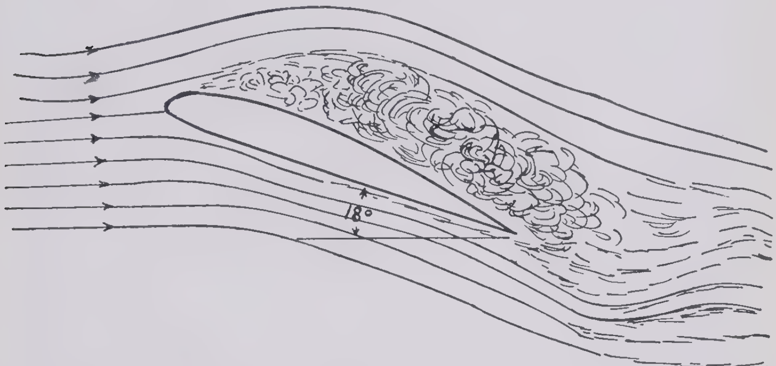


FLOW AROUND A WING INCLINED AT 10 DEGREES

FIGURE 35

As the angle of inclination increases, so will the deviation of the air. The lift will increase, but so will the drag.

Finally, at a sufficiently large angle, the lift will reach a maximum value. Since the flow is now thoroughly disturbed, any further increase in inclination will actually cause a decrease in lift and an increase in drag. This point of maximum lift is termed the "burbling" or "stalling" angle, and stalling bears a great importance to safety in flying.



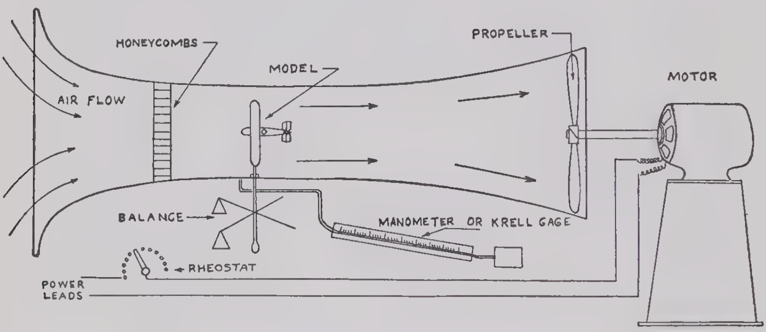
FLOW AROUND A WING INCLINED AT 18 DEGREES

FIGURE 36

There is quite a technique in the visual or photographic study of flow. Sometimes water is made to flow past a surface, with coloring matter, or skim milk, or aluminum powder introduced into the stream, so that the actual flow can be photographed. When air is the medium investigated, a jet af acetylene may be carefully introduced into the general flow system. The acetylene has optical properties differing from that of the surrounding air, and hence can be photographed. Again an electric heating coil can be introduced into the air stream and the heated air photographed. Nothing is so instructive as such visual or photographic study. "Seeing" the flow is not sufficient however; we have to measure the forces involved.

Measuring Forces in the Wind Tunnel

The wind tunnel is based fundamentally on the principle of relative motion which states, as we have already seen, that a stationary object with air moving by at a certain speed will have identical forces acting on it as an object moving through the air at that speed. It would be very inconvenient, almost impossible to measure forces on gliding models. It is much easier to hold the model at rest and force the air to flow past it, and this is actually done in the wind tunnel, which is used to determine the aerodynamic characteristics (such as lift, drag and center of pressure) of flat plates, air foil sections, and complete airplane models.



DIAGRAMATIC SKETCH OF A WIND TUNNEL
FIGURE 37

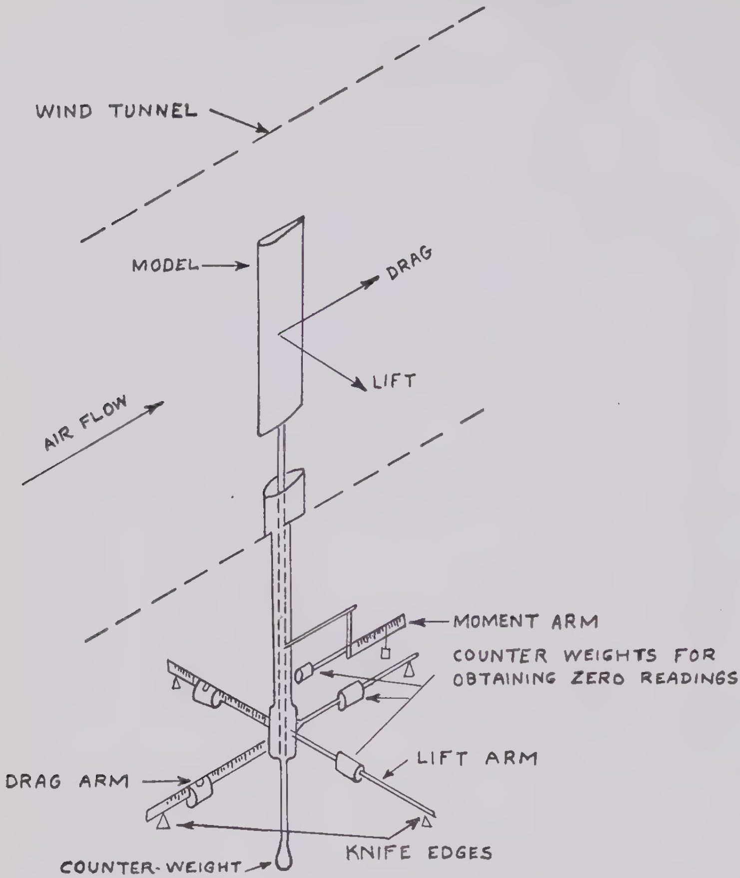
A diagramatic sketch of a wind tunnel is shown in Figure 37. The propeller at the right end is rotated by means of an electric motor and kept at any desired speed. This propeller draws the air from the tunnel and thrusts it out into the room. The air at the other end of the tunnel then rushes in through the entrance cone. This cone is very large at the open end and tapers down gradually in a smooth curve as it approaches the working section. A smooth curve is necessary to prevent the air from becoming turbulent as the area of the section is

decreased. The working section has a small area so that we can obtain a high wind velocity without using too powerful a propeller. Between the entrance cone and the working section is a honeycomb which looks like an automobile radiator from the front. This together with the curved wall keeps the air flow smooth and straight. From the working section out, the tunnel gradually enlarges in diameter up to the propeller, as a large propeller slowly rotating is found most efficient for wind tunnel work.

The velocity of the wind in the tunnel is measured by means of a Krell gage. This is merely a long inclined tube whose lower end is connected to a reservoir of alcohol. The upper end of the tube is connected to the wall of the tunnel. As the wind passes by, it sucks some of the air out of the tube and the liquid in the reservoir rises in the other end of the tube. The greater the speed of the tunnel the more the suction and the higher the rise of the liquid. A graduated glass tube is used so that the exact height of the liquid may be observed at any particular wind speed. By the aid of Bernouilli's law, the velocity can be readily calculated.

The model is set up in the working section. It is supported on a spindle attached to a balance or weighing machine as shown in Fig. 38. The model is generally supported in the tunnel as though it were flying on its side. The air forces acting on the model are not affected and may be measured more readily with this arrangement. The lift and drag forces are measured by two arms on the balance placed at right angles to each other. The circular disk shown is graduated in degrees and the spindle may be rotated to obtain any desired angle of attack on the model. Readings are usually made of lift and drag for every two degrees within the working angles of the airplane. Curves are then plotted which give the characteristics throughout the entire range.

The measured forces on the small model may be suitably scaled-up to give the forces on a full-sized plane. We have found that the lift and drag are proportional to density, area and velocity squared. The area of the model is known from



WIND TUNNEL BALANCE

FIGURE 38

its dimensions and the velocity of the air in the tunnel is determined by the gage as previously explained. Suppose we have an airfoil section of ½ sq. ft. area being tested at 40

m.p.h. in the tunnel. Suppose the lift force reading to be 1 lb. and the drag 1/12 lb. Let us find the lift and drag on such an airfoil which at full size has an area of 300 sq. ft. and flies at 80 m.p.h.

$$\frac{\text{Lift full scale}}{\text{Lift of model}} = \frac{(\text{Area} \times \text{Velocity}^2) \text{ full scale}}{(\text{Area} \times \text{Velocity}^2) \text{ of model}}$$

$$= \frac{300 \times 80^2}{\frac{1}{2} \times 40^2} = 2400.$$

Therefore the lift full scale is 2400 times the lift of the model.

Thus 2400×1 lb. $= 2400$ lb. $=$ lift full scale.

And the drag likewise $= 2400 \times 1/12$ lb. $= 200$ lb.

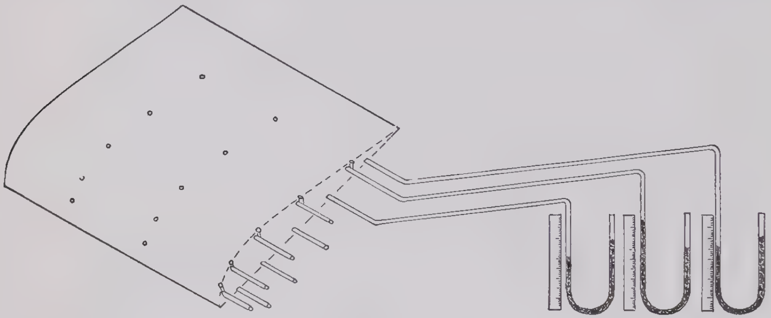
The center of pressure location on the model is not always directly above the spindle and the resultant force then tends to turn the model around the spindle. The resultant twisting moment about the spindle is measured down below by weights on the moment arm. As we know the resultant force for any angle from our lift and drag readings, we can compute the distance from the spindle at which this force must be acting to cause a given twisting moment. This distance then determines the center of pressure for a particular angle of attack.

Models may be tested quickly and cheaply in the tunnel and such tests give accurate results. Changes in the model may be made and modifications tested at a very small expense. This is particularly important in obtaining the required stability for a new design. To make such modifications by cut and try, on the full-sized airplane, is dangerous and costly.

Pressure Distribution Round a Wing

Still another important method of experimentation in aerodynamics is the study of pressure distribution. Fig. 39 indicates diagramatically the method employed in studying a wing. Tubes are led along the upper and lower surface of the wing, with small openings flush with the surface. The tubes are con-

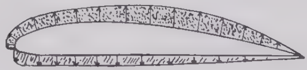
nected with a series of gages or manometers. All the holes, except those actually being studied, are closed up with wax or cigarette paper. The readings of the manometers are photo-



DIAGRAMATIC SKETCH SHOWING METHOD FOR MEASURING PRESSURE DISTRIBUTION.
FIGURE 39

graphed. It is possible by suitably arranging the holes, and opening up a certain number at a time, to study the pressure at any cross-section of the wing, and also along its span.

Fig. 40 shows the pressure distribution for a typical wing at a small angle of attack, on both the upper and lower surface.



PRESSURE DISTRIBUTION FOR A WING AT A SMALL ANGLE OF ATTACK
FIGURE 40

This pressure distribution diagram is very instructive. It indicates first of all, that it is the suction of the upper surface of the wing which contributes the major portion of the lift. The second conclusion is that at small angles of attack, it is the rear

portion of the wing which has the greater concentration of force acting on it. At large angles of attack, the concentration of force and the center of pressure evidently move forward.

Properties of Flat Plates

Force measurements in the wind tunnel confirm the deduction already made from visual studies, that a flat plate is aerodynamically inferior to a cambered airfoil.

The outstanding characteristics of flat plates are as follows:

a. The maximum efficiency or L/D ratio is only 7.6 (as compared with as much as 20 for a good airfoil).

b. The lift is zero at zero angle of attack and reaches a maximum at about 30 degrees angle of attack. The maximum K_y value obtainable is approximately .00206. This value is comparable with that of medium lift wing section.

c. As might be expected, the center of pressure moves from the leading edge at zero degrees to 50 per cent of the chord at 90 degrees.

There is a structural reason also for the unsuitability of a flat plate, and that its lack of thickness. It is impossible to house in a flat plate a wing spar of sufficient strength.

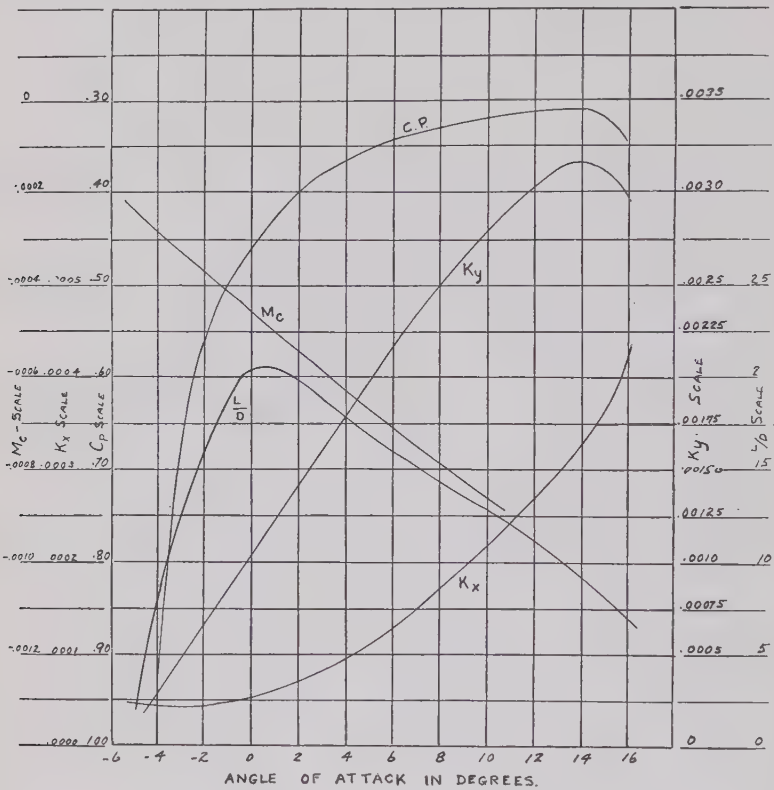
Properties of a Typical Wing Section

In Fig. 41 we have drawn the outline of the Clark Y, an excellent and typical wing section. The aerodynamic character-

CLARK Y WING SECTION
FIGURE 41

istics of this section are plotted in Fig. 42. These curves were obtained by testing a 36 x 6 inch model in the tunnel at a wind speed of 40 m.p.h., and include the lift and drag coefficients, the L/D and the position of the center of pressure all plotted against angle of attack.

The curves of lift and drag plotted against angle of attack correspond to what might be expected from a study of the sketches of air flow. As the angle of attack increases the flow



CHARACTERISTIC CURVES FOR CLARK Y AIRFOIL
FIGURE 42

of air is deflected more and more from its original path and both lift and drag are increased. The Clark Y section reaches its "burble" point at 14 degrees. It can be seen from the curve that beyond 14 degrees, the lift falls off quite sharply.

It should be noted that the lift coefficient is not zero, at zero angle of attack. It would only be zero for a flat plate, or a symmetrical double cambered section, because even at zero incidence, there is still present a deviation of the air flow. It is only at —5 degrees incidence, when the nose is well down that the lift becomes zero.

Another important point to be noted on the curves is the minimum K_x or drag coefficient. A small value of the minimum K_x is particularly important for high speed planes, which fly at small angles of incidence in the region of top speed. The minimum K_x of the Clark Y is only .000035.

The point of maximum L/D, whose value is 21 occurs around 1 degree, whereas the angle of minimum K_x is about —3 degrees, at which angle the K_y is too small to give a high L/D ratio.

A pilot always lands his plane at the angle corresponding to the maximum lift, so as to land as slowly as possible. The Clark Y is quite an efficient wing, with its maximum L/D of 21, but its maximum K_y is only moderate in value—namely .00318.

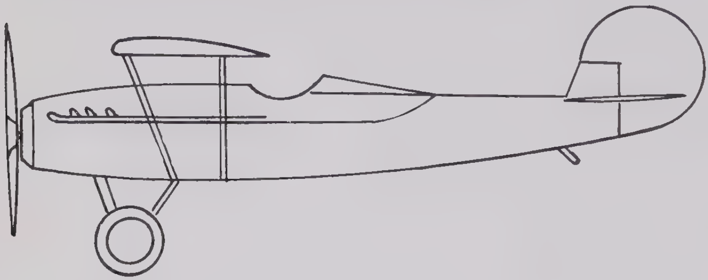
The center of pressure movement of the Clark Y agrees with what we would deduce from the curves of pressure distribution. At high angles of incidence, it moves forward with 30.5 percent of the chord from the leading edge as its most forward position. As the angle of incidence diminishes, the center of pressure moves backward. As we shall see later, too sharp a movement of the center of pressure is undesirable both from a stability and a structural point of view.

Simple Relations Between Wing Lift, Drag and Speed

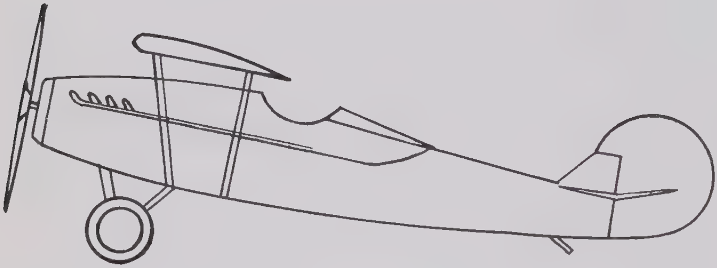
If a plane with a constant weight and area is to fly slowly it must fly at a large angle, where its coefficient of lift is large, to make up for the loss of lifting capacity due to the slow speed. Thus when a plane lands it is flying at a slow speed and a large angle of attack. The drag at large angles is great and slows the plane up quickly after landing.

If the same plane is to fly fast it must fly at small angles. Here the drag is very small and although the coefficient of lift

is likewise small, the greater velocity supplies the necessary lifting force to maintain flight. The attitudes when flying fast and when flying slow are illustrated in Fig. 43.



ATTITUDE OF PLANE WHEN FLYING FAST



ATTITUDE OF PLANE WHEN FLYING SLOW

FIGURE 43

Some simple equations for wing lift, drag and speed may be written as follows:

To maintain horizontal flight the lift on the wings of an air-

plane must equal the weight of the plane (W). The equation $L = K_y A V^2$ then becomes:

$$W = K_y A V^2$$

This can be expressed in four useful forms:

$$(1)\quad K_y = \frac{W}{AV^2}$$

$$(2)\quad V = \sqrt{\frac{W}{K_y A}}$$

$$(3)\quad A = \frac{W}{K_y V^2}$$

$$(4)\quad \frac{W}{A} = K_y V^2.$$

From these equations we can deduce with greater assurance the fundamental relations between the speeds and angles of attack at which an airplane is flown, remembering that for any airplane the weight and area are constant.

When the speed V is large it follows from equation (4) that K_y must be small which can only be at a small angle of attack. At high speeds the angle of attack is in the vicinity of zero degrees.

When landing, the pilot flies the ship as slowly as possible. Thus V is small and K_y must be large which means an angle of attack near the burble point of the particular wing used.

At "cruising speed," when above everything efficiency is sought the pilot flies the plane as near the angle of greatest efficiency (best L/D) as possible.

It also follows that if a machine has a very large wing area for its weight, it will land slowly and fly slowly. On the other hand a small area relative to its weight indicates a fast flying ship. Thus transport planes have large wings and racers very small wings.

The drag of a wing $D = K_x AV^2$. In horizontal flight $L = W$.
Then $L/D = W/D$

when $W = D(L/D)$, and $D = \dfrac{W}{(L/D)}$ for an airplane.

Or in other words the drag of a wing or an airplane at any particular angle of attack is equal to the weight of the plane divided by the L/D ratio at that angle.

Example

A monoplane with Clark Y wing has an area of 200 square feet and flies at 80 miles per hour at an angle of attack of 6 degrees. What is the weight of the airplane and the drag of the wing?

From Fig. 10, $K_y = .00215$ at 6 degrees.

$W = K_y AV^2 = .00215 \times 200 \times 80^2 = 2752$ pounds.

$L/D = 16$ at 6 degrees.

$$\text{Drag of wing} = \frac{W}{L/D} = \frac{2752}{16} = 172 \text{ pounds.}$$

Questions and Problems

1. Define "burble point." At about what angles do ordinary wings burble?
2. What is K_y? In what units is it expressed?
3. Why does a plane land at a large angle of attack?
4. A wind tunnel model of a Clark Y airfoil has an area of 18×3 in. = 54 sq. in. It is to be tested at 40 m.p.h. What will be the lift on the model at an angle of attack of 6 deg.?
5. A 200 sq. ft. wing of Clark Y section is designed to land at 50 m.p.h. What weight can it support? (Use K_y maximum.)
6. A monoplane with a Clark Y wing has an area of 200 sq. ft. and flies at 80 m.p.h. at an angle of attack of 10 deg. What is the weight of the airplane? The drag of the wing?
7. If the wing of an airplane has a 6 foot chord, and a Clark Y wing, how far from the leading edge will the center of pressure be at (I) 12 degrees incidence (II) 4 degrees incidence.

Answers

1. The burble point of a wing is that point where its lift is a maximum. Most ordinary wings burble between 12 and 18 deg.

2. K_y is the coefficient of lift in Engineer's Units. It is expressed as lb. per sq. ft. per m.p.h.

3. A plane lands at a large angle of attack because at those angles K_y is large and flight can still be maintained even though the speed is very small.

4. 1.29 lb.

5. 1590 lb.

6. W = 3540 lb. D = 272 lb.

7. (I) 22.3″.
   (II) 26.3″.

CHAPTER VI

ELEMENTS OF PERFORMANCE CALCULATION. PLANE, PROPELLER, AND ENGINE CO-ORDINATION

In our last chapter, we presented the characteristics of a typical wing, the Clark Y, a section of excellent aerodynamic properties. There is no "best" wing known to designers but there are a large number of good wings to select from, and there is always some wing best fitted for a particular design. The student may be anxious to learn of good wings other than the Clark Y, and to approach the interesting subject of wing selection. This will be dealt with in a later chapter; it is better to study first of all the simple, theoretical elements of airplane performance, which serve largely as a basis for wing selection.

Wing Horse-Power

In our first chapter we defined work as force $\times$ distance. The term horse-power was defined as the rate of work done in a given period of time, 550 foot-pounds per second, 33,000 foot-pounds per minute. In airplane work, the force is expressed in pounds, the speed in miles per hour. This introduces a difficulty, which can however be easily surmounted.

Suppose that the drag of an airplane wing is D_w pounds, and the speed is V miles per hour. The speed in feet per second is then

$$\frac{V \times 5280}{60 \times 60} = \frac{V \times 5280}{3600}$$

The work per second in overcoming the drag of the wing is therefore $\dfrac{D_w \times V \times 5280}{3600}$. Since horse-power is 550 foot-

pounds per second, the horse-power required is therefore

$$\frac{D_w \times V \times 5280}{3600} \times \frac{1}{550}$$

which cancels out to $\dfrac{D_w V}{375}$.

We have thus derived the important formula $P_w = \dfrac{D_w V}{375}$

where P_w is the power required by the wing
D_w is the drag of the wing in pounds
and V is the speed in miles per hour.

It is sometimes convenient to use an alternative form introducing the drag coefficient of the wing, and its area.

$$D_w = K_x\,(AV^2)$$

Substituting in the previous equation, we get

$$P_w = \frac{D_w V}{375} = \frac{(K_x\,AV^2)\,V}{375} = \frac{K_x(AV^3)}{375}$$

There is another convenient formula for the wing horse-power, based on the fact that the drag of the wing $D_w = \dfrac{W}{L/D_w}$ where W = weight of the airplane and L/D_w is the efficiency ratio of the wing.

$$\text{Hence } P_w = \frac{D_w V}{375} = \frac{W}{L/D_w} \times \frac{V}{375}$$

Characteristics of Clark Y in Tabular Form

In the last chapter we presented some curves for Clark Y charactertistics. Sometimes it is handy to have them in tabulated form as follows:

Angle of Attack in Degrees	K_y	K_x	L/D
−6	−.0001	.000041	−2.44
−4	.0003	.000039	7.7
−2	.00068	.000040	17.0
0	.00105	.000051	20.6
2	.00140	.000070	20.0
4	.00178	.000100	17.8
6	.00214	.000132	16.2
8	.00251	.000173	14.5
10	.00276	.000219	12.6
12	.00301	.000268	11.22
14	.00320	.000323	9.92
16	.00300	.000431	6.96

Example

A monoplane of 200 square foot wing area, Clark Y wing section, carries a load of 1600 pounds. What are the speed, wing drag and wing horse-power when flying at 2 degrees angle of incidence?

At 2 deg. $K_y = .00140$. $K_x = .000070$

$$V = \sqrt{\frac{W}{K_y\ A}} = \sqrt{\frac{1600}{.00140 \times 200}} = 76 \text{ m.p.h.}$$

$$D_w = K_x\ (AV^2) = .000070 \times 200 \times 76^2 = 81 \text{ pounds}$$

$$P_w = \frac{D_w\ V}{375} = \frac{81 \times 76}{375} = 16.42 \text{ horsepower}$$

Curves of Wing Drag and Wing Horse-Power

When curves of wing drag and wing horse-power are required through the flying range, calculations are tabulated as follows (these apply to the monoplane just described):

TABLE I

Speed M.P.H.	V^2	$K_y = \frac{W}{AV^2}$	i = Angle of Incidence	K_x from Tables or Curves	$D_w = K_x AV^2$	$P_w = \frac{D_w V}{375}$
60	3600	.00222	6.2°	.000143	100.1	16
70	4900	.00163	3.3°	.0000820	80.2	15
80	6400	.00125	1.1°	.0000588	75.2	16
90	8100	.00099	−0.25°	.0000494	80.0	19.2
100	10000	.00008	−5.2°	.0000445	89.1	23.8

The curves of wing drag and wing horse-power are plotted in Fig. 44 against the speed in miles per hour. The angles of incidence are also indicated on these curves, as a matter of general interest.

From these curves a number of interesting points are apparent:

1. As the angle of incidence goes to a negative value and the K_y becomes very small, the velocity becomes very great. If we could fly at an infinitely small K_y, the velocity would become infinitely great. Of course this is a purely theoretical conception, because there would not be sufficient horse-power to fly at tremendously high speed.

2. There is a definite minimum speed corresponding to the angle of maximum K_y. Beyond this angle the speed increases again.

3. The least wing drag occurs at about 80 miles per hour, at an angle of incidence of about zero degrees. This is the angle of best or maximum L/D. We might have expected this since

$$D_w = \frac{W}{L/D_w}.$$

4. Below the speed of best L/D, the wing drag increases fairly slowly up to the "stalling" speed. Beyond the stall, the

speed increases. The efficiency of the wing drops off and the wing drag rises very sharply.

5. In studying the curves of wing horse-power, we notice that the minimum horse-power occurs at a lower speed and a larger angle of incidence than the point of minimum drag,

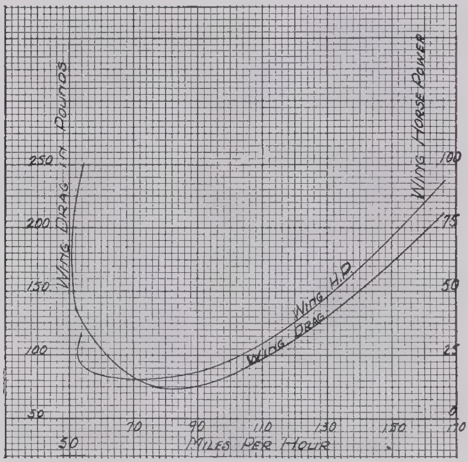


Figure 44

namely at 70 miles per hour and approximately 3 degrees incidence.

6. At small angles and high speeds the wing horse-power increases rapidly since efficiency goes down as speed goes up. It also increases rapidly at stalling speeds, where the curve bends back on itself.

Parasite Drag and Parasite Horse-Power

The parasite drag of an airplane is the drag of all its parts other than the wing, namely, fuselage, landing gear, struts, wires, etc.

The parasite drag may be denoted by the symbol D_p, and we can write

$$D_p = K_p V^2$$

where D_p = parasite drag of the airplane in pounds
K_p = parasite drag coefficient in pounds per mile per hour.
V = speed in miles per hour.

The parasite drag coefficient of an airplane changes much less markedly with the attitude of the airplane, than the drag coefficient of the wing. For example, it is evident that the drag of the landing wheels will depend solely on the speed and not on the flying attitude of the airplane. Diehl in his "Engineering Aerodynamics" classifies the following items as having drag coefficients independent of the angle of attack of the wings: "struts, wires, fittings, wheels, tail skids, air-cooled engines, radiators, and fuselages having circular or elliptical cross-sections." Such items as floats, hulls, tail surfaces, and fuselages of square or rectangular section vary in drag coefficient with angle of attack.

The increase in the parasite drag coefficient is, however, most marked at high angles of incidence and slow speed, when both drag and horse-power required become less important to us. Therefore in estimating performance, the parasite drag coefficient is very often considered to be a constant.

It is sometimes convenient to refer the parasite drag coefficient to the wing area.

The equation for D_p then becomes

$$D_p = K_p V^2 = K_p A V^2$$

where K_p is the parasite drag coefficient in pounds per square foot of wing area per mile per hour $= \dfrac{K_p}{A}$

The equation for parasite horse-power becomes:

$$P_p = \frac{D_p V}{375} = \frac{(K_p V^2) V}{375} = \frac{K_p V^3}{375}$$

$$\text{or } P_p = \frac{D_p V}{375} = \frac{(K_p AV^2) V}{375} = \frac{K_p AV^3}{375}$$

The equation for total drag becomes

$$D_t = D_w + D_p$$
$$= (K_x + K_p) AV^2$$

and the equation for total power becomes

$$P_t = P_w + P_p$$
$$= \frac{(K_x + K_p) AV^3}{375}$$

In estimating the parasite drag of an airplane, the drag coefficient of each part has to be found, and all these values added together. Errors are introduced because of interference between parts. The resistance of wheels and landing gear struts tested together in the wind tunnel may be greater than the sum of the resistances of the same wheels and struts tested separately, because at the point where struts and wheels adjoin, there may be constriction of the air flow. The parasite drag is therefore frequently estimated from the test of a complete tunnel model, by subtracting the wing drag from the total drag of the model. Sometimes the parasite drag is obtained in similar fashion from a full flight test.

Example

The monoplane previously mentioned of 200 square feet wing area, Clark Y wing, 1600 pounds gross weight, is found on test to have a maximum speed of 130 miles per hour and is equipped with a 110 horse-power engine. If the efficiency of the propeller is 80% at maximum speed, what are

(a) parasite horse-power at 130 miles per hour
(b) parasite drag at 130 miles per hour
(c) parasite drag coefficient
(d) parasite drag coefficient referred to wing area?

(a) At top speed, the efficiency of the propeller is 80%, therefore the power delivered to the airplane is

$$\frac{110 \times 80}{100} = 88 \text{ horse-power.}$$

The wing horse-power at top speed is 50 horse-power.

Therefore the parasite horse-power is $88 - 50 = 38$ horse-power.

(b) Parasite Horsepower $P_p = \dfrac{D_p V}{375}$.

$$\text{or } 38 = \frac{D_p (130)}{375}$$

$$\text{So that parasite drag } = \frac{38 \times 375}{130} = 109.5$$

(c) $D_p = K_p V^2$

$109.5 = K_p (130)^2$

$$\text{and } K_p = \frac{109.5}{130^2} = .0065$$

(d) $K_p = \dfrac{K_p}{A} = \dfrac{.0065}{200} = .0000325.$

Curves of Parasite Drag and Parasite Horse-Power

When once the parasite resistance coefficient is known and provided it is assumed to remain constant with angle of attack, it is easy to calculate for every speed the parasite drag from the formula

$$D_p = K_p V^2$$

and the parasite horse-power from the formula

$$P_p = \frac{D_p V}{375}$$

The results of these calculations are shown in the curves of Fig. 45.

From these curves it is evident that at low speeds, the parasite drag is much less than the wing drag, and the parasite horse-power much less than the wing horse-power. At high

speeds the inequality diminishes. From this we deduce that for fast machines "cleanness" of design is more important than for slow machines.

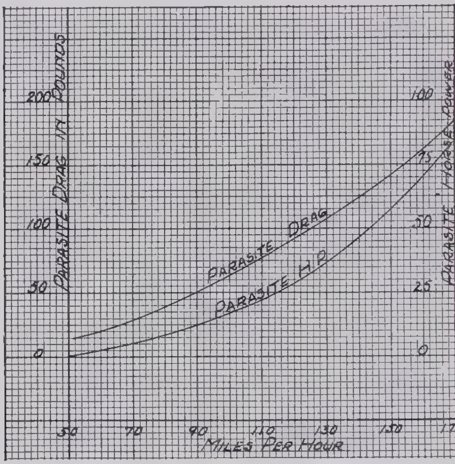


FIGURE 45

Curves of Total Drag and Total Horse-Power

In Fig. 46 the curves of Fig. 44 and Fig. 45 have been compounded to give curves of total drag and total horse-power.

The minimum total drag is about 112.5 pounds and occurs at 2 degrees, a somewhat higher value than the minimum drag point of the wing alone. Neglecting considerations of engine speed and propeller efficiency, this point would give the condition for the least work in flying a given distance, since work = force × distance. In trying for a distance record with a given quantity of gasoline, the pilot would theoretically fly at this angle of incidence of 2 degrees.

The minimum total horse-power is about 20 and occurs at about 4 degrees, again a somewhat higher value than the mini-

mum horse-power point of the wing alone. Again neglecting considerations of engine and propeller, this would be the correct point to fly for maximum endurance in time, as distinct from maximum endurance in distance.

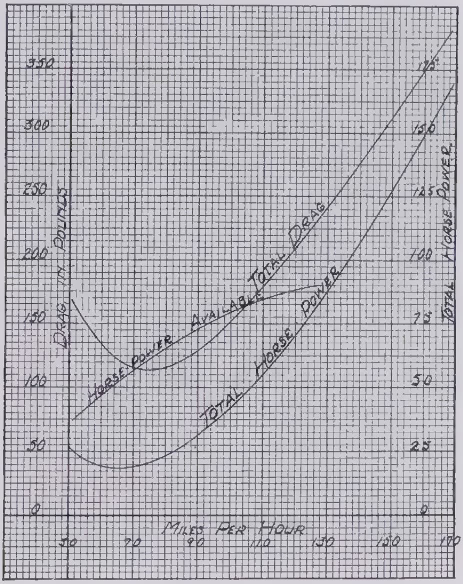


Figure 46

Direct Calculation of Total Drag and Total Horse-Power

For purposes of instruction, we calculated the curves of wing drag and horse-power separately from the curves of parasite drag and parasite horse-power. But if the parasite resistance coefficient is known, all the curves can be made in one table as follows:

TABLE 2

Speed V M.P.H.	V^2	$K_y = \frac{W}{AV^2}$	K_x from Tables or Curves	K_p	Total Drag $D_t = (K_xK_p) AV^2$	Total H.P. $P_t = \frac{D_tV}{375}$
60	3600	.00322	.000143	.0000325	124.2	19.85
70	4900	.00163	.000082	.0000325	112.1	20.95
80	6400	.00125	.0000588	.0000325	116.8	24.90
90	8100	.00099	.0000494	.0000325	132.6	31.80
100	10000	.00008	.0000445	.0000325	154.0	41.15
etc.						

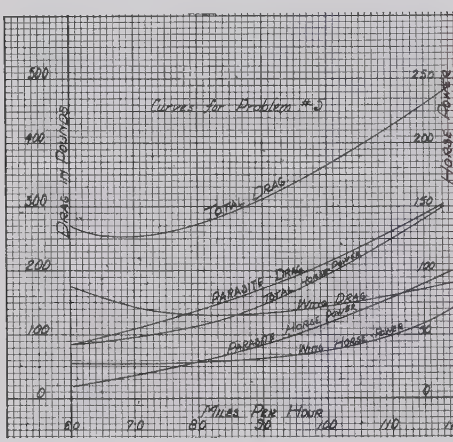


FIGURE 47

Equivalent Flat Plate Area

For purposes of comparison, the parasite resistance is sometimes expressed in terms of the equivalent flat plate area. In

the monoplane as given described in the previous problem, what will be the equivalent flat plate area?

The parasite drag at 130 m.p.h. was 109.5 pounds.

Let A_e be the equivalent flat plate area, whose resistance coefficient is .0032. Then $.0032 \times A_e \times 130^2 = 109.5 = K_p \times 130^2$ and $A_e = 2.03$ square feet, which is a very low figure, and shows that our monoplane is extremely well streamlined.

The same result would be obtained by writing

$$A_e = \frac{K_p}{.0032} = \frac{.0065}{.0032} = 2.03.$$

We shall often compare machines on the basis of their equivalent flat plate areas.

Overall Efficiency of an Airplane

The overall efficiency is given by the expression

$$\frac{W}{D_t} = \frac{K_y AV^2}{(K_x + K_p) AV^2} = \frac{Ky}{K_x + K_p}$$

The L/D of the entire machine will, at any angle, always be less than the L/D of the wing alone, depending on how large is the K_p or parasite resistance coefficient referred to wing area.

Computation of Horse-Power Available

After the total power required has been found, it is necessary to find the horse-power available at various plane speeds. The horse-power available is the net horse-power delivered to the plane and is equal to the horse-power of the engine multiplied by the efficiency of the propeller. The computation is somewhat complicated because the power of the engine varies with the revolutions per minute, the revolutions per minute vary with the forward speed of the plane and the efficiency of the propeller varies with the ratio of forward speed of the plane to the rotational speed of the propeller.

We shall carry the computations through step by step, and in the process will have to learn something of the characteristics of the engine and of the airplane propeller.

From the difference between the power available and the power required, we can get the excess power and hence the climb.

Horse-Power R. P. M. Curve of a Typical Engine

When an engine has been built, it is tested by the Department of Commerce in order to receive an approved type certificate, and a curve of horse-power against revolutions per minute is obtained in the laboratory. A typical curve is shown

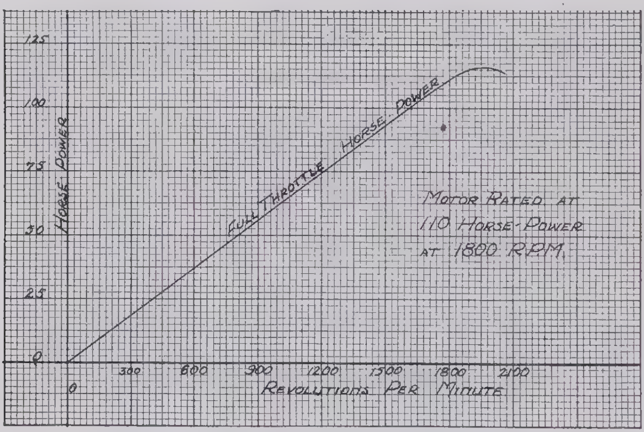


Figure 48

in Figure 48, for an engine which is rated at 110 horse-power at 1800 revolutions per minute.

It can be seen from this curve that this curve is practically a straight line from the origin as might be expected. At full throttle, and not too high a speed, the power developed in each complete cycle, (inlet stroke, compression stroke, firing or power stroke and exhaust gas) is practically constant.

Therefore the greater the revolutions per minute, the greater the horse-power developed.

When the engine is near its very highest speed, however, with the piston moving and the valves closing and opening very rapidly, it becomes harder to get the full charge into the cylinders in the short time available. Hence, beyond a certain number of revolutions per minute, the power of the engine actually begins to fall off, as indicated in the curve of Figure 48.

Fundamental Principles of the Airplane Propeller

It was one of the great achievements of the Wright brothers to formulate a simple, sufficiently accurate theory of the airplane propeller. They based their theory on the supposition that each element of a propeller blade behaved just like an airfoil.

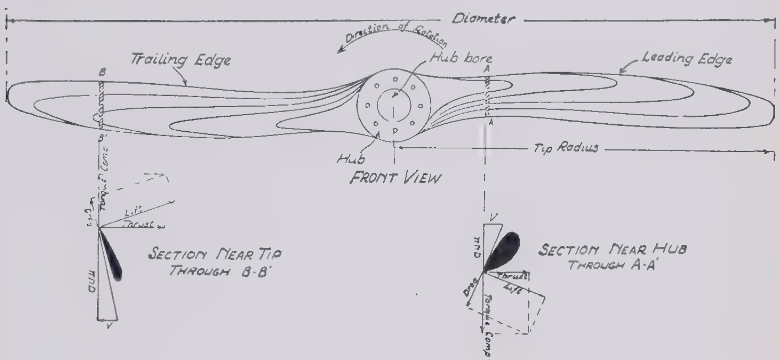


FIGURE 49

Figure 49 shows the plan view of a typical tractor propeller (made of wood), as seen by a man standing in front of the airplane, and rotating in an anti-clockwise direction as seen by him. When seen from the cockpit, this propeller will appear to rotate in a clockwise direction, and is said to be a right-hand propeller, as are most of the tractor propellers used to-

day. A propeller is said to be a tractor when it is pulling ahead of the engine. When a propeller is placed behind the engine, it is said to be a pusher. Pusher propellers are very frequently used on flying boats, where it is inconvenient in docking to have a propeller swinging in front of the wings. Figure 49 illustrates the main terms used in designating parts of a propeller. If we take a section on the left hand blade of Figure 49, looking from the left, and turn it into the plane of the paper, we see the shape of the blade element, similar to that of an ordinary airfoil. The propeller blade element has two relative winds acting on it, the wind due to the forward speed of the airplane and the relative wind due to the rotation of the propeller. The resultant wind makes an angle with the plane of rotation, which is somewhat less than the blade angle. The angle between the resultant wind and the surface of the blade evidently determines the angle of incidence at which the propeller works. Since the efficiency of an airfoil is greatest at an angle of incidence of about 2 degrees, that propeller will be most efficient, all other things being equal, which is working at an incidence of about 2 degrees. The blade angle of the propeller also has an important influence on the efficiency.

Since the element of a propeller blade is working just like an airfoil, it will have lift and drag acting on it. The lift will act at right angles to the resultant wind, and the drag will act along the resultant wind. Examining the diagram of Figure 49 closely, and resolving the lift and drag into the plane of rotation and along the line of flight, we see that

I The lift produces most of the thrust.

II The drag decreases the thrust.

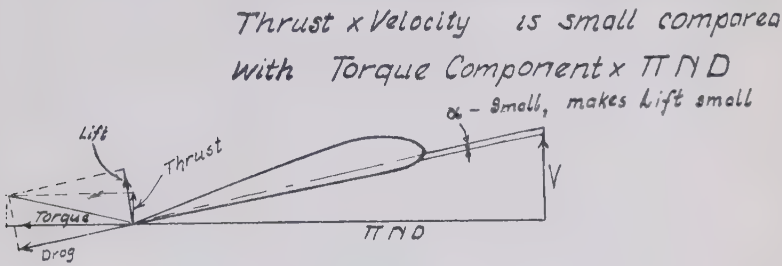
III A small portion of the lift tends to oppose the rotation of the propeller.

IV A large proportion of the drag tends to oppose the rotation of the propeller.

The forces which oppose rotation evidently have a moment about the center of the propeller shaft, which must be overcome by the torque or turning moment of the engine.

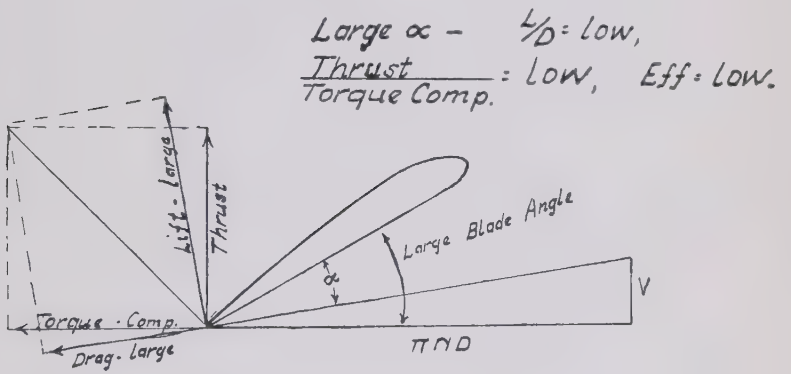
The effective work done on the plane must be proportional to thrust times the velocity, T × V.

The work done in turning the propeller must be proportional



SMALL BLADE ANGLE VECTOR DIAGRAM

FIGURE 49A



LARGE BLADE ANGLE VECTOR DIAGRAM

FIGURE 49B

to the resultant force or torque force component in the plane of rotation multiplied by the rotational velocity (πnD).

Now if the blade angle is very flat, as in Figure 49 (a), the

angle of incidence will be very small. The lift will be small. Also the product of Thrust by V will be small as compared

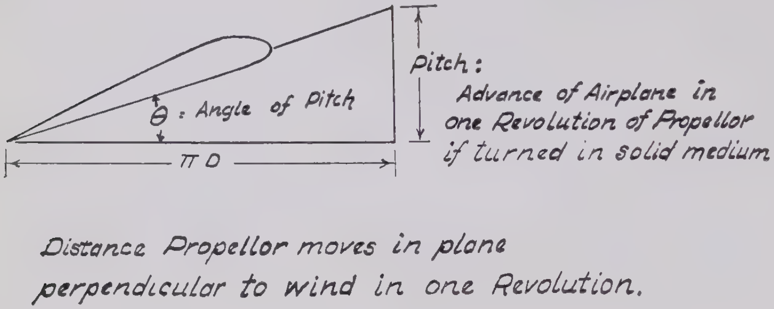


FIGURE 49C

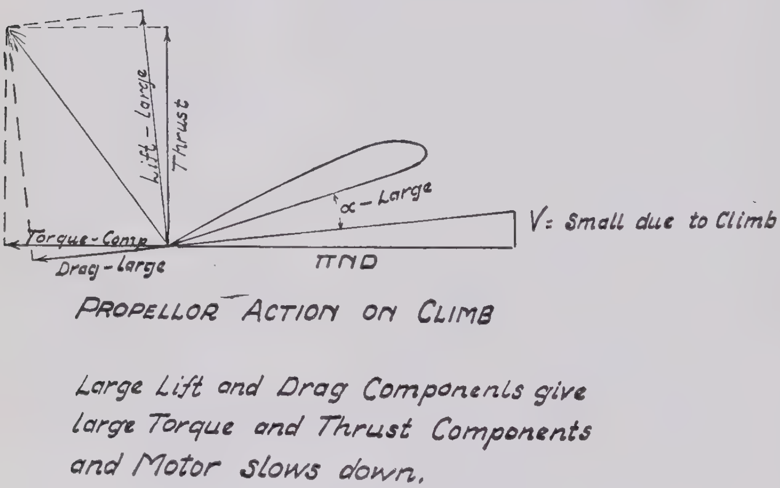


FIGURE 49D

with the product of Torque Component by πnD. Hence the efficiency will be very low.

If the blade angle is very large, as in Figure 49 (b), the efficiency will again be very small, because the angle of inci-

dence will be excessive and the L/D of the section correspondingly low.

Therefore there must be, for a given set of conditions, a best setting of the blade, neither too large nor too small. This can be determined by trial and error, or by a fairly simple mathematical process.

The blade angle is evidently the sum of the angles between the resultant wind and the plane of rotation, and the angle of incidence.

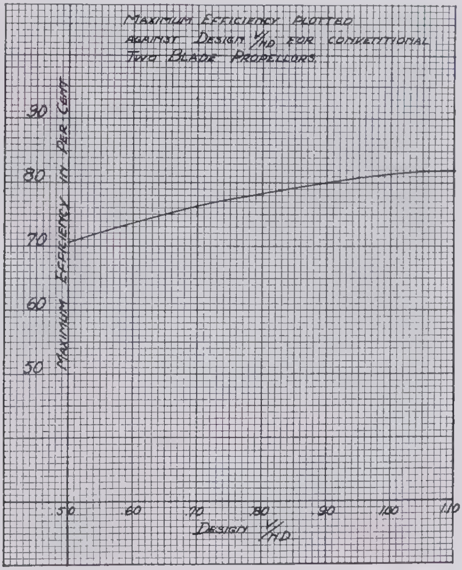


FIGURE 50

The tangent of the angle between the resultant wind and the plane of rotation is given by $\dfrac{V}{\pi nD}$. The ratio $\dfrac{V}{nD}$ therefore gives us an idea of the blade angle, and is very frequently

used by aeronautical engineers as a definition of the working conditions of a propeller.

While propellers vary somewhat in design, yet if correctly designed in conventional two-bladed form, they always have about the same efficiency at the same value of the V/nD. In Figure 50 there is plotted a curve of propeller efficiency against V/nD at the top speed of the airplane which represents the average values of efficiency to be hoped for. This curve is derived from a series of wind tunnel tests.

At very low values of V/nD the blade angles become too small and the efficiency drops off.

As the V/nD increases, the blade angle increases and so does the efficiency. It is only when the V/nD exceeds 1.10 that the efficiency starts dropping off again. At this V/nD the blade angle at the tip will be about 21 degrees, allowing 2 degrees incidence for the blade element. At two-thirds radius the blade angle will be 30 degrees; the blade angles increase progressively from tip to hub.

Finding the Propeller Efficiency in Our Performance Calculations.

In the particular plane for which we are making performance calculations, the estimated top speed is 130 miles per hour or 130×1.467 feet per second. The revolutions per minute of the motor are 1800. From past experience it has been found that the following is a good formula for the diameter of a two-bladed dural propeller.

$$D = \sqrt[4]{\left(\frac{K^2}{\text{r.p.m.}}\right)^2 \cdot \frac{B\,H\,P}{V}}$$

where an average value of $K^2 = 90{,}000$. Hence

$$D = \sqrt[4]{\left(\frac{90000}{1800}\right)^2 \cdot \frac{110}{130}} = 6.8 \text{ ft.}$$

and the diameter of our propeller is approximately 7 feet.

We can now find the V/nD.

$$\frac{V}{nD} = \frac{\text{speed in feet per second}}{\text{revolutions per second} \times \text{diameter in feet}}$$

$$= \frac{130 \times 1.467}{\frac{1800}{60} \times 7} = .908$$

Now turning back to the curve of Figure 50, we find that the corresponding efficiency is 80%. That is an important step forward in our calculations.

Some Ideas of Pitch

On the flying field we will often hear a remark such as this—"That prop is very good; it's got a high pitch." It seems of interest to examine this idea of pitch. Suppose we consider the motion of a propeller blade element, as if it were moving in a solid. Its motion will then be as if it were moving along a huge screw. For each revolution the element would advance a certain amount and this advance would be the pitch. As illustrated in Figure 49 (c), the $\frac{\text{pitch}}{\text{circumference}}$ = tangent of the blade angle. We have seen that the efficiency is largely dependent on the blade angle. Hence the efficiency is not dependent on the pitch, but on the ratio of the pitch to the circumference of the cylinder on which the propeller element is moving.

We should always have the blade angle 2 or 3 degrees greater than the angle whose tangent is $\frac{V}{\pi nD}$ so that the blade is working at the most efficient angle of incidence.

Hence when $\frac{V}{nD}$ is large, we can have a large blade angle and a large pitch.

For a machine of great flying speed, as compared with the tip speed of its propeller, we can have a large pitch therefore.

But if a high pitch propeller is put on a slow speed machine, in preference to a low pitch propeller, the chances are that the propeller efficiency will be diminished, because there will be incorrect co-ordination.

The pitch is generally measured on the propeller at two-thirds of the blade radius out from the center of the shaft.

Example

A 9-foot propeller, turning at 1800 revolutions per minute, is used on a plane whose maximum speed is 120 miles per hour. What would be a reasonable pitch to have at two-thirds of the radius?

At two-third radius, the rotational speed of the element is

$$\pi nD = \pi \times \frac{1800}{60} \times 6 = 565 \text{ feet per second.}$$

Since the diameter is only 6 feet at two-third radius.

The forward speed is $120 \times 1.467 = 176$ feet per second.

The tangent of the angle between the wind due to rotational speed and the wind due to forward speed is therefore $\frac{176}{565} = .312$. From a book of trigonometric tables, we find that the corresponding angle is 17.3 degrees. Adding 2 degrees to this the blade angle is 19.3 degrees, and tan $19.3 = .3502$.

$$\text{Hence } \frac{\text{pitch}}{\pi \times 6} = .3502$$

$$\begin{aligned} \text{pitch} &= .3502 \times \pi \times 6 \\ &= 6.6 \text{ feet} \end{aligned}$$

which seems like a reasonable value.

Another way of considering pitch is to calculate the $\frac{\text{Pitch}}{\text{Diameter}}$ which in this case is $\frac{6.6}{9} = .735$.

For a fast machine the pitch/diameter ratio is likely to be bigger than for a slow machine.

Why an Engine Slows Down on the Climb

The plane speed on the climb is of course much less than the maximum speed in level flight, because not only has drag to be overcome but also the pull of gravity. The engine slows down some 100 revolutions or more.

The explanation of this slowing down is quite simple. Referring to the diagram of Figure 49 (d), if the forward speed should diminish and the rotational speed not change, the angle

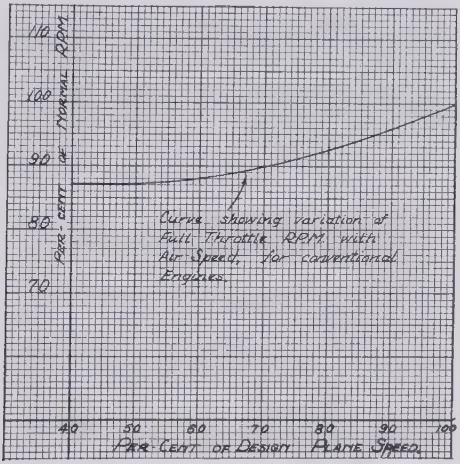


FIGURE 51

between the resultant wind and the plane of rotation becomes quite small. Since the blade angle remains fixed, the angle of incidence at which the blade element is working would become very large. This would mean more lift and drag on the element; hence more thrust and more torque. But the torque or turning moment of the engine has not become larger just because we are climbing. Hence the engine on the climb cannot

swing the propeller at the high revolutions per minute possible in level flight, even if the throttle is kept full open.

Figure 51 shows the way in which the propeller revolutions drop off, as the speed drops off at full throttle.

Why Propeller Efficiency on the Climb Is Less than at Top Speed

We can also readily explain why the propeller efficiency on the climb falls off.

The propeller is generally designed to be most efficient at its top speed. The blade angle is so arranged that at top speed the angle of incidence is at its most suitable value of 2 degrees or thereabouts. On the climb, the forward speed is reduced considerably, while the rotational speed is reduced only a little. Hence the angle of incidence of the blade element is increased beyond the angle of best L/D and at the same time the propeller is now working at a smaller value of $\frac{V}{nD}$. Both facts lead to a decrease in efficiency.

There is also another reason why the efficiency on the climb decreases. Fundamentally the thrust of a propeller is produced by accelerating the air backwards as it passes through the propeller disk area. The slipstream in back of the propeller always has a greater velocity than the speed of the plane therefore. Now more speed means more kinetic energy, and the increase in kinetic energy of the air in passing through the propeller disk area constitutes an aerodynamic loss. The thrust on the climb is much greater than at top speed, because, as previously stated, the thrust has to overcome a gravity component as well as the air resistance.

Therefore the air on the climb receives more acceleration in going through the propeller disk area, and there is more kinetic energy loss in the slipstream and less propeller efficiency.

The curve of Figure 52 shows how the efficiency of the pro-

peller diminishes as its working V/nD becomes a smaller fraction of the design V/nD, or V/nd at top speed.

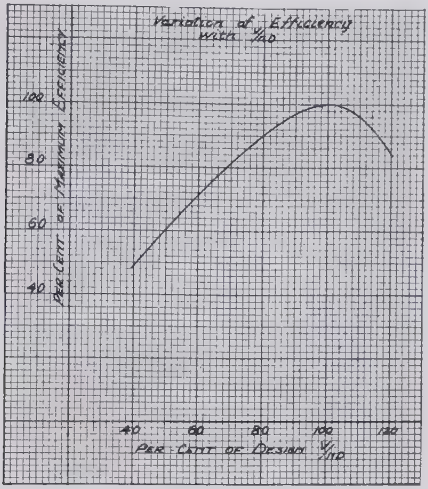


FIGURE 52

Continuation of Calculations for Power Available Curve

We are now in a better position to continue our calculation of the power available curve, as in Table 1.

In column (1) we put down assumed velocities.

In column (2) we put down the percent of the design or maximum speed. From the curve of Figure 52 we find to what percent of the design r.p.m. the propeller has slowed down and tabulate in column (3).

We then find the r.p.m. by multiplying the design r.p.m. by the percentage of column (3) and thus obtain the figures of column (4).

Then from the curve of Figure 48, giving the characteristics of the engine, we get the actual horse-power delivered to the propeller at full throttle and at the particular air speeds considered.

TABLE 1

Design N = 1800 R.P.M.
Design V = 130 M.P.H.

(1) Velocity in Miles Per Hour	(2) Percent of Design Velocity	(3) Percent of Design R.P.M.	(4) N in R.P.M.	(5) H.P. Delivered to Prop.
50	38.4	87.0	1568	94
70	53.7	87.5	1578	96
90	69.2	88.8	1600	99
110	84.5	94.0	1692	106
130	100.0	100.0	1800	110

Design N = 1800 R.P.M.
Design V = 130 M.P.H.

The calculation is now continued as in Table 2, which is merely a continuation of Table 1.

We see that column (6) is the same as column (1) and column (7) is the same as column (4).

Column (8) is obtained by calculating V/nD for each speed by the formula given:

Column (9) is obtained by dividing column (8) by the design V/nD and multiplying by 100.

Column (10) is obtained by finding the values of percentage of maximum efficiency from Figure 52 corresponding to values in column (9).

Column (11) is the product of column (10) and the maximum efficiency, 80.0%.

Column (12) is the product of column (11) and column (5) and is equal to the net power delivered by the propeller at each speed.

These values are plotted as horse-power available in Figure 46.

TABLE 2

Maximum Efficiency = 80%
Design N = 1800 R.P.M.
D = 7 feet
Design V = 130 M.P.H.
Design $\frac{V}{nD}$ = .908

(6) Velocity in Miles per Hour	(7) N in Revolutions per Minute	(8) V/nD	(9) Percent of Design V/nD	(10) Percent of Maximum Efficiency	(11) Efficiency	(12) Horse Power Available
50	1568	.40	44.2	54	43.2	40.6
70	1578	.59	61.5	73	58.4	56.2
90	1600	.71	71.0	82	65.7	65.0
110	1692	.82	90.2	97	77.7	82.5
130	1800	.91	100.0	100	80.0	88.0

$$\frac{V}{nD} = \frac{\text{V (in miles per hour)} \times 88}{\text{D (diameter in feet)} \times \text{(in revolutions per minute)}}$$

It is because this curve of power available crosses the total power required curve at 130 m.p.h. that we know this to be the top speed.

We see that at lower speeds, with engine all out; the power available is in excess of the power required. For equilibrium the difference must be taken up in climb.

As we have learned in previous chapters, in climb, the excess horse-power goes into doing work against gravity. For example, at 90 miles per hour the excess horse-power is 73.5 — 31.8 or 41.7, which is equal to 41.7 × 33,000 foot pounds per

minute. Since the weight of the airplane is 1600 pounds, the climb in feet per minute is $41.7 \times \frac{33000}{1600} = 861$ feet per minute.

It is a noteworthy fact that in the case of most modern machines, there is excess horse-power at the minimum speed of the plane. Excess horse-power at minimum speed of the plane provides a measure of safety against "stalling," since the pilot can then pull his plane out of a stall by letting out the engine and beginning to climb.

Changing a Propeller in the Field

There has been an enormous amount of work done on the propeller, both theoretical and experimental. Nevertheless there always remains some uncertainty as to whether the best propeller has been designed for a given plane and engine. On important new designs as many as twelve different propellers may be tried out in flight before final selection is made.

The practical operator, also, may not be satisfied with the propeller he has purchased with his plane and wish to try out some modified forms on his own account.

It is futile and expensive however to try out new propellers at random, and perhaps the following hints will help:

a. *Engine will not turn up full r.p.m. at high speed and speed is disappointing.*

The pitch and blade angles may be correct, but perhaps the propeller diameter is too large. Try same pitch and a smaller diameter.

b. *Engine turns up full r.p.m. at high speed, but speed is less than might reasonably be expected.*

The pitch and blade angles may be too small. In this case the angle of incidence at high speed may be too small, and the propeller is not delivering its proper thrust. The remedy is to increase the pitch and blade angles. Some-

times this will tend to hold down the r.p.m. Then try a propeller with larger pitch and smaller diameter, or larger pitch and a trifle narrower blade.

c. *Engine races at high speed.*

Try same pitch, but a larger diameter propeller.

d. *Climb is less than might reasonably be expected.*

A propeller which has just the right pitch at top speed may be very inefficient on the climb, because its pitch is then too high for the slow forward speed. (That is why there may be two propellers for a given plane, one a speed propeller and the other a climb propeller. That is why also a variable pitch propeller is likely to be of so much value in improving performance.) The remedy is to decrease the pitch slightly and perhaps increase the diameter. Decreasing the pitch will give better co-ordination on the climb. Increasing the diameter means less slipstream velocity at heavy thrust, hence less loss in the slipstream, and again an increase in efficiency.

e. *Twin-engined plane will not fly on one engine.*

When one engine fails, the other engine has to work at full r.p.m. and much lower forward speed. Therefore, its pitch becomes too high (just as on the climb). If a propeller more suitable for the single-engine condition is selected, that may make all the difference between flight on one engine and failure to fly on one engine.

f. *Poor take-off.*

At take-off, the thrust is high and slipstream losses are large. At the same time the angle between the relative wind and the plane of rotation is small. Therefore, improvement in take-off will follow if a lower pitch and larger diameter are employed.

In general for high speed, large pitch, small diameter; for climb and take-off, lesser pitch and larger diameter.

Advantages of Metal Propellers

Dural propellers are rapidly coming into use and displacing wooden propellers. Metal propellers have the advantage of greater durability and resistance to hitting by rain or gravel, and also avoid the use of such an uncertain material as glue. They are apt to run heavier than wooden propellers for the same service, but this is more than compensated for by their greater aerodynamic efficiency.

With metal propellers using a material of higher density and greater strength, the centrifugal forces are greater than for wooden propellers. When the propeller deflects under the thrust, the centrifugal force relieves the bending moment more effectively than in a wooden propeller. Therefore dural propellers can be built with much thinner sections than the wooden propellers. Thinner sections are likely to be more efficient than thick sections, and dural propellers for a given service may have five to seven per cent more efficiency than wooden propellers. At very high tip speeds, approaching the speed of sound, the efficiency of thick sections drops off very badly, while for thin sections the drop is less pronounced. Therefore, for large and very high speed engines the dural propeller is likely to show an even greater advantage in efficiency as compared with the wooden propeller.

Problems

1. A monoplane has a wing area of 300 square feet, Clark Y and is loaded 9 pounds per square foot. What is the minimum speed?

2. (a) What will be the incidence for minimum wing drag? (b) What will be the speed at minimum wing drag? (c) What will be the minimum wing drag?

3. The maximum speed desired is 120 m.p.h.

(a) What will be the wing horse-power at this speed?

(b) If the engine is 200 horse-power and the propeller efficiency is 78 per cent, what will be the horse-power available at top speed?

(c) How much horse-power will be left over to overcome parasite drag?

(d) What will be the wing drag at top speed?

(e) What will be the parasite drag?

(f) What will be the parasite resistance coefficient referred to wing area?

(g) What will be the equivalent flat plate area of the airplane?

4. Assuming the parasite resistance coefficient to be a constant, what will be the overall L/D of the airplane at (a) 0 degrees incidence? (b) 8 degrees incidence? Plot a curve of L/D against angle of attack for the entire airplane. Does the best L/D of the whole airplane occur at a smaller or larger angle than for the wing alone? Explain your result.

5. Plot curve of (a) wing drag; (b) wing horse-power; (c) parasite drag; (d) parasite horse-power; (e) total drag; (f) total horse-power. See Fig. 47.

6. Draw an approximate curve of horse-power available, assuming that at 70 m.p.h. the available horse-power is only half that at maximum speed. What is the maximum excess power? What is the maximum rate of climb in feet per minute?

7. A plane will fly at about 120 miles per hour with an engine that delivers 100 horse-power at 2000 revolutions per minute. What size propeller should be used?

8. What is the V/nD of the propeller of problem 7?

9. What is its maximum efficiency?

10. If the plane shoud fly at 100 miles per hour, at what r.p.m. would the propeller be turning? What would be the V/nD in this case? What is the efficiency in this case?

Answer.

1. $A = 300$

$w/A = 9$

$K_y max$ for Clark Y $= .00323$

$$V \text{ min.} = \sqrt{\frac{W}{K_y max\ A}} = \sqrt{\frac{1}{K_y max}\ \frac{W}{A}}$$

$$= \sqrt{\frac{1}{.00323} \times 9}$$

$= 53$ m.p.h.

2. (a) From Fig. 42 minimum wing drag occurs at $-3°$

(b) Min. $Kx = .00004$ at $-3°$

$Ky = .00045$

$$V = \sqrt{\frac{W}{A}\ \frac{1}{K_y}} = \sqrt{\frac{9 \times 1}{.00045}}$$

$V = 141$ m.p.h.

(c) $D = Kx\ AV^2$

$= .00004 \times 300 \times 141^2 = 239\#$

3. Vmax $= 120$ m.p.h.

(a) $L = Ky\ AV^2$

$$\frac{L}{AV^2} = \frac{W}{AV^2} = K_y$$

$$\frac{9}{(120)^2} = \frac{9}{14400} = .000625 = K_y$$

at $-2.3°$ $K_x = .000041$

$D = K_x\ AV^2$

$= .000041 \times 300 \times (120)^2 = 177\#$

$$\text{Wing HP} = \frac{DV}{375} = \frac{177 \times 120}{375} = 56.8 \text{ hp.}$$

(b) $200 \times .78 = 156$ h.p. available

(c) H.P. left over to overcome parasite drag $156 - 56.8 = 99.2$ h.p.

(d) Wing drag = 177#

(e) $\text{h.p.} = \dfrac{D_p V}{375}$

$$99.2 = \frac{D_p\, 120}{375}$$

$D_p = 310\#$ Parasite Drag

(f) $A = 300$

$D_p = 310\#$

$V = 120$

$$K_x = \frac{D}{AV^2} = \frac{310}{300} \times (120)^2 = .0000717$$

(g) Equivalent Flat Plate Area $D = .0032\, A_e V^2$

$D = 310 + 177 = 487\#$

$$V = 120;\quad \frac{D}{.0032V^2} = A_e$$

$$= \frac{487}{.0032 \times 120^2} = 10.55 \text{ sq. ft.}$$

4. At 0° incidence $K_y = .00105$

(a) $K_x = .000051$

$L = K_y AV^2$

$$\frac{L}{K_y A} = V^2 = \frac{9}{.00105} = 8560$$

$$V = 92.4$$

$D_{wing} = K_x AV^2 =$

$= .000051 \times 300 \times 92.4^2 =$

$= 131\#$

$D_{parasite} = .0032 \times 6.74 \times 92.4^2 =$

$= 185\#$

$D_{total} = 131 + 185 = 316\#$

$$\text{Overall } L/D = \frac{2700}{316} = 8.55$$

(b) 8° incidence $K_y = .00250$
$K_x = 00017$

$$V^2 = \frac{L}{K_y\ A} = \frac{9}{.00250} = 3600$$

$V = 60$ m.p.h.

$D_{wing} = 00017 \times 300 \times 3600 = 183\#$

$D_{parasite} = 0032 \times 6.74 \times 3600 = 77.6$ lbs.

D_{total} 260.6# total

$$L/D = \frac{2700}{259.6} = \underline{10.4}$$

The best L/D of the whole airplane occurs at a larger angle than that for the wing alone. Since the total drag is higher than that for wing alone, more lift is needed and this can only be obtained at a higher angle of incidence.

PROBLEM 5

Velocity M.P.H.	Wing Drag K_xAV^2	Wing H.P. $=\frac{DV}{375}$	Parasite Drag $= .0032 \times 6.74\ V^2$	Parasite H.P. $= \frac{D_pV}{375}$	Total Drag $D_t = D_w\ D_p$	Total H.P. $= HP_w\ HP_p$
60	183	29.2	77.6	12.4	260.6	41.6
70	146	27.3	105.7	19.7	251.7	47.0
80	130	27.7	138.0	39.4	268.0	57.1
90	132	31.7	174.8	42.0	306.8	73.7
100	148	39.5	216.0	57.6	364.0	97.1
110	163	47.8	261.0	76.7	424.0	124.5
120	177	68.0	311.0	99.2	488.0	157.2

(6) Left to reader.

(7) $D = \sqrt[4]{\left(\frac{90{,}000}{2000}\right)^2 \times \frac{100}{120}} = 6.4$ feet.

(8) $V/_{nD} = \dfrac{120 \times 1.467}{\dfrac{2000}{60} \times 6.4} = .823$

(9) Maximum efficiency for propeller with design V/nD of .823 from figure 50 equals 78.8%.

(10) 100 m.p.h. $= \dfrac{100}{200} = .832$ design V $= 83.2\%$

From figure 51 the percentage of design N is 94.0%

$$94 \times 200 = 1880 \text{ r.p.m.}$$

$V/_{nD} = \dfrac{100 \times 1.467}{\dfrac{1880}{60} \times 6.4} = .73$

$.73 = \dfrac{.73}{.823}$ of design $V/_{nD} = 88.8\%$ $V/_{nD}$ design.

From figure 52, the propeller less 96% of its design efficiency or $.96 \times 78.8 = 75.6\%$ efficiency.

CHAPTER VII

ELEMENTS OF AIRPLANE MECHANICS

A knowledge of airplane mechanics is a necessary foundation for both pilots and aeronautical engineers. In the following article we shall deal with only a few of the simplest but most essential problems.

Gliding

In Figure 53 is shown an outline of an airplane on a glide. With power shut off, it is subjected to only three forces: lift, drag and gravity. If there is to be a steady glide at a constant speed, then these three forces must balance one another or be in equilibrium as the mathematicians say. Suppose that the glide path makes an angle with the horizontal. The relative wind is along the glide path and of opposite direction to the motion. Then the lift must be perpendicular to the glide path, the drag must act along the glide path; and gravity acts vertically downwards.

By the principles of mechanics stated in the first chapter, we can resolve the force of gravity W along and perpendicular to the glide path as shown in the diagram.

The force along the glide path will be Wsin θ, and this must evidently balance the drag. Hence we get the equation

$$W \sin \theta = D_t = (K_x + K_p)\, AV^2$$

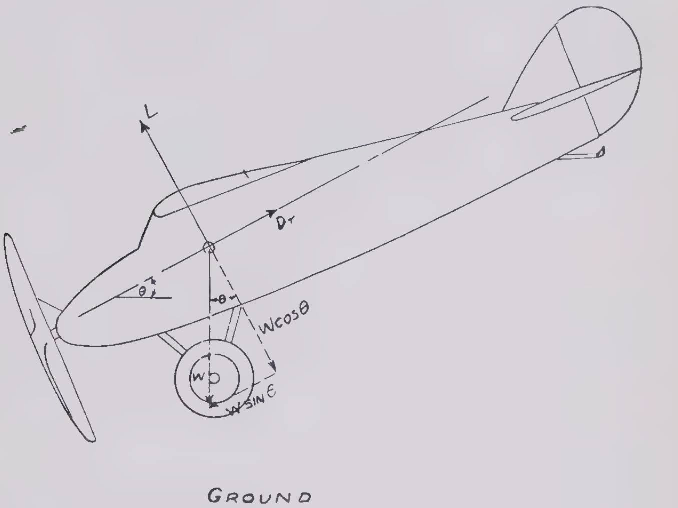
by the previous chapter.

The force perpendicular to the glide path will be $W \cos \theta$, and this must evidently balance the lift. Hence we get the equation $W \cos \theta = L = K_y AV^2$. Dividing these equations one by the other, we get

$$\frac{W \sin \theta}{W \cos \theta} = \tan \theta = \frac{D_t}{L} = \frac{(K_x + K_p)\, AV^2}{K_y AV^2} = \frac{K_x + K_p}{K_y}$$

It follows from this that the greater the L/D_t or efficiency ratio of a plane, the flatter will be the angle of glide.

A flat angle of glide is an advantage from the point of view of a pilot seeking an emergency landing, since it gives him a longer gliding range.



FORCES IN A GLIDE

FIGURE 53

Pilots in reporting on the behavior of some machines state that they "float" when approaching the ground, and that a landing is made difficult thereby. No very plausible explanation of floating has been offered hitherto. A possible explanation is that with a wing fairly close to the ground, ground interference makes itself felt in two ways: increase in lift coefficient and increase in lift over drag. If the plane is efficient to begin with, the floating tendency is readily understood. The author believes that a remedy is always available to the pilot who can simply bring the plane in at an angle of incidence, giving a poor lift over drag ratio.

It should be noted that the angle of glide is dependent solely on the lift over drag ratio of the plane and not on the wing loading. If the glide angles of two exactly similar planes, one of which is more heavily loaded than the other, are compared, they will be found to be exactly the same. The only difference will be that the heavily loaded plane will glide faster than the lightly loaded one.

Since the angle of glide depends on the lift/drag ratio, it follows that a glide can be made at any desired angle to the horizontal between 90 degrees and the angle of flattest glide. Further, for each angle of incidence of the wing, there will be a corresponding lift/drag and hence a corresponding angle of glide.

Example

In the plane considered in the previous chapter, the monoplane wing area was 200 square feet, the wing section was a Clark Y, the gross weight was 1600 pounds and the parasite resistance coefficient was .0000325 referred to the wing area.

If the wing is at 6 degrees, incidence to the flight path, what will be

(a) The angle of the glide path with the horizontal?
(b) The speed on the glide?
(c) The radius of glide from an altitude of 5000 feet?

(a) At 6 degrees incidence, the K_x of the wing is .000132 (see Table in Chapter 6), and the K_y is .00214.

$$\text{Therefore } L/D_t = \frac{K_y}{K_x + K_p} = \frac{.00214}{.000132 + .0000325.}$$

$$= \frac{.00214}{.0001645} = 13 \text{ (approximately)}$$

$$\text{Hence } \frac{D_t}{L} = \frac{1}{13} = \tan\theta \text{ (where } \theta \text{ is the angle of glide)} = .077.$$

Looking up the angle corresponding to this tangent in a table

of trigonometric functions, we find it to be 4°24′ or 4 degrees and 24 minutes.

(b) To find the speed on the glide we use the equation

$$W \cos\theta = K_y AV^2$$

In this case, $\cos\theta = .9970$ (approximately) so that $1600 \times .9970 = .00214 \times 200 \times V^2$

$$\text{and } V^2 = \frac{1600 \times .9970}{.00214 \times 200} = 3720.$$

and $V = 61$ miles per hour.

$$\text{(c) From Fig. 54 we see that } \tan\theta = \frac{\text{altitude}}{\text{radius of glide}}$$

$$\text{In this case therefore } .077 = \frac{5000}{\text{radius of glide}}$$

and the radius of glide is 65,000 feet.

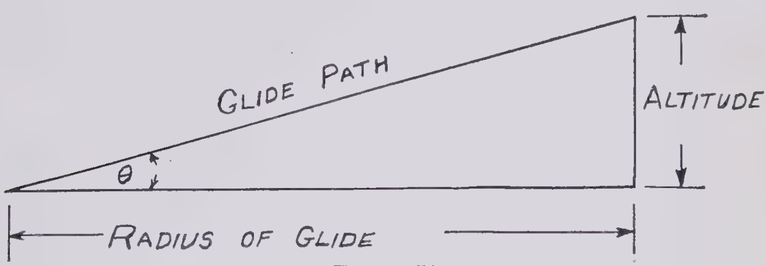


FIGURE 54

We selected for our calculations a particularly well streamlined machine. Normally the glide path will be much steeper. A best glide of one in twelve may be considered quite good.

In Fig. 55, from calculations similar to those just made, we have plotted a curve of angles of glide against the incidence of the wing and the speed in miles per hour.

From this curve we see that the best angle of glide of 4°15′ occurs at 3° angle of incidence.

The angle of glide increases on either side of this point.

It appears therefore that the pilot can make a glide of the same steepness at two different angles of incidence and two different speeds along the path.

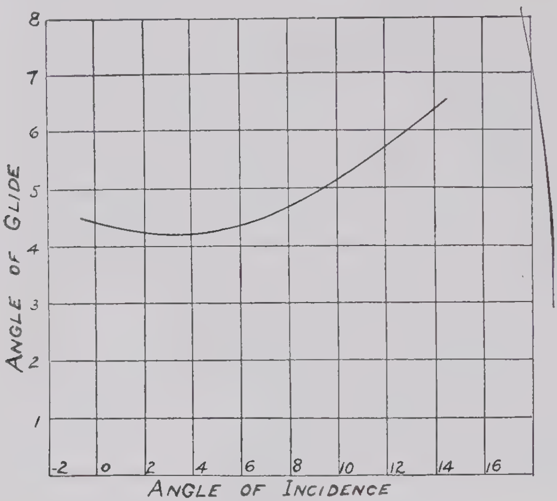


FIGURE 55

Gliding Into a Small Field

When making an emergency landing into a small field, particularly when surrounded by obstacles such as trees or telegraph wires, the question arises as to the best way of landing. There are some methods such as coming down in a tight spiral, side slipping, fish tailing (i.e. swinging the tail of the plane from side) which in the hands of a skilled pilot are perfectly safe and very effective in losing altitude in a small horizontal distance of travel. Such methods however are evidently not suitable in passenger carrying work.

If the pilot does not wish to adopt the above mentioned methods, he can glide down at high speed and on a very steep path, and flatten out quickly just before reaching the ground. There are two difficulties here. Firstly, real judgment has to

be exercised in flattening out at just the right instant. Secondly, if the pilot does flatten out at the right instant, his plane will still have a high rate of speed. If he flattens out to a high angle of incidence, and a large coefficient of lift, the plane may "zoom" that is climb rapidly into the air for a second or two and then drop rather suddenly and uncomfortably. Evidently zooming and then dropping will not be pleasant. If on the other hand, the plane is flattened out to a relatively small angle of incidence, the landing speed will be high and while there will be no tendency to zoom, the plane will run for a long distance on the ground, which is still a serious difficulty in a small field.

It may be that in modern practice, pilots will be able to adopt another method of procedure, namely the "stalled" glide, that is a steep glide at a high angle of incidence, with the nose of the plane above the horizon.

For example in the hypothetical plane we are dealing with, suppose the pilot elects to glide in at 16 degrees angle of incidence.

$$\text{the } L/D_t = \frac{.00300}{.000431 + .0000325} = \frac{.00300}{.0004635} = 6.5$$

The glide is therefore just twice as steep as in the flattest glide, and the angle with the horizontal is given by

$$\tan\theta = \frac{1}{6.5} = .154 \text{ and } \theta = 8°45'.$$

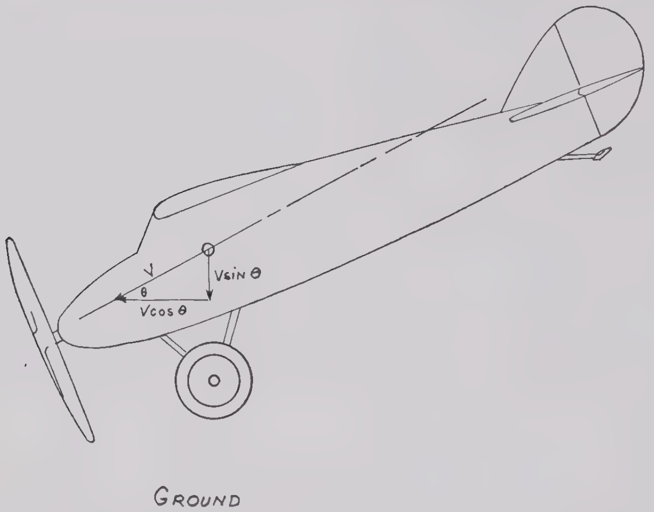
Since the wing is at 16 degrees to the glide path, it will be $16° - 8°45' = 7°15'$ above the horizon.

There is therefore little risk of nosing into the ground or of nosing over, and the pilot can easily set his ship down in a good three point landing (that is front wheels and tail skid touching the ground simultaneously).

When flattening out from a flat glide at small angle of incidence, the lift coefficient is increased so much that all the vertical velocity of the plane is killed. A well executed three

point landing can be perfectly gentle, without the semblance of a shock.

Since the stalled glide is made at a high lift coefficient, it is impossible to kill the vertical speed entirely by going to the



VELOCITY IN A GLIDE.

FIGURE 56

maximum lift coefficient. It is interesting to see what this vertical speed is.

From the formula

$$W \cos\theta = K_y \, A V^2$$

$$W \cos 8°45' = 1600 \times .0983 = .003 \times 200 \times V^2$$

$$V^2 = 2630$$

and $V = 51.3$ miles per hour.

From Fig. 56, we see that the vertical velocity of the plane on the glide path is $V \sin\theta$. In this case $\sin\theta = .1521$ and the vertical velocity is $51.3 \times .1521 = 7.80$ miles per hour.

A landing with such vertical velocity might seriously dam-

age the landing gear, or the fuselage at the points where the landing gear attaches.

Stalled glides to the ground have been achieved in many machines without serious damage. Nevertheless if a stalled glide is to become a common method of getting into a small field, airplane designers will have to provide more shock absorber travel to take up the vertical velocity.

Lateral control at the stall will also have to be improved. This we shall have occasion to discuss in a later chapter.

Vertical Nose Dive

It might be thought at first glance that if a plane is put into a vertical nose dive as shown in Fig. 57, with no lift at all on the wings, the downward speed would become tremendously high. When the machine is first put into a nose dive, the acceleration is indeed very high, but with increase of speed the drag of the wings and the parasite resistance increase also till they balance the entire weight of the airplane. Then there is no further downward acceleration and the plane comes down steadily at its terminal velocity.

Referring again to our hypothetical plane, the lift of the wing will be zero at a negative angle a little beyond—4 derees, and the K_x of the wing is then .00004.

In the vertical nose dive, since gross weight now equals drag, we can write

$$W = (K_x + K_p)\ AV^2$$
$$1600 = (.00004 + .0000325)\ 200\ V^2$$
$$\text{and } V = 332 \text{ miles per hour.}$$

Of course we are working with a particularly clean machine. The diving speed would be much less for the ordinary plane.

We can rewrite the above formula in a more convenient form

$$V^2 = \frac{W}{A\ (K_x + K_p)}$$

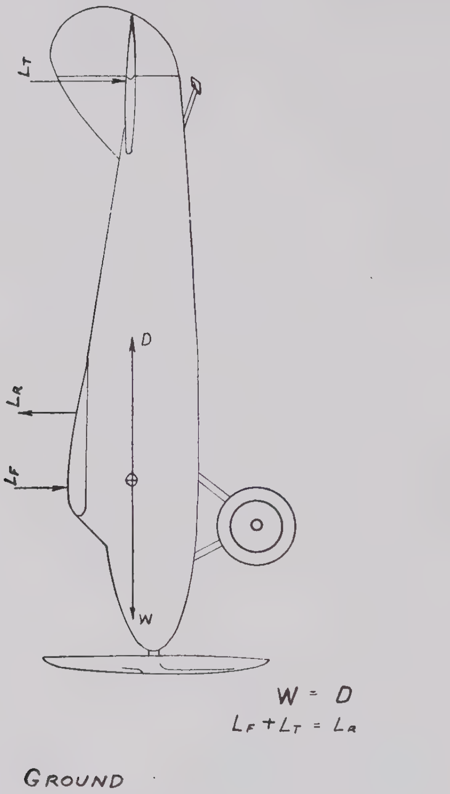
From this formula we see that the terminal velocity will

(a) increase with the loading per square foot.

(b) increase as the drag of the wing at no lift diminshes.

(c) increase as the parasite drag coefficient diminishes.

There is no record of the maximum diving speed ever attained. We should imagine that for a racing plane capable of



FORCES IN A VERTICAL DIVE.
FIGURE 57

300 miles top speed, the terminal diving speed would be well over 400 miles per hour.

The action of the propeller in a nose dive is rather curious. In the first stages of the dive the propeller thrust evidently in-

creases the acceleration. But later when the speed goes well above the maximum speed of the plane, the propeller blade elements will be working at negative angles and the propeller will be actually working as a brake rather than as a thrust producing element.

The reader may ask whether the vertical nose dive is dangerous. When the wings are at zero lift, the whole weight of the plane has to be supported by the drag truss of the wing; which must be strong enough to meet the load. Further, at zero lift, there is a twisting moment or couple on the wings, which brings a large downward force on the front spar and a large upward force on the rear spar. The wing must be designed to resist this twisting or torsion of the wings. The elevator must supply an adequate counter balancing couple or else the machine will go over on its back, and it must be powerful enough to get the machine out of the dive whenever the pilot wants to. Naturally the vertical nose dive must not be practised too near the ground. Where the greatest danger arises however is when the pilot pulls out of the dive too sharply. The wing may then go from a low lift coefficient to a high lift coefficient too quickly, with enormous lift loads ensuing. We shall go into greater detail into this question of loads in a later chapter.

Equilibrium in Steady Horizontal Flight

In Chapter 1, we discussed the question of equilibrium of forces and moments. For an airplane in steady horizontal flight, we must have:

(a) the sum of the lift forces equal to the weight.

(b) the thrust of the propeller equal to the sum of the drag forces of all the parts of the plane.

(c) the moment of all forces about the center of gravity equal to zero.

In Fig. 58, this equilibrium of forces and moments is illustrated for another hypothetical airplane. The plane is supposed to be flying at zero degrees of incidence, with the center of pressure well behind the center of gravity. The lift on the

wing is therefore tending to nose the plane down. Accordingly the elevator has to be turned up, so that the tail surfaces carry a downward load L_t.

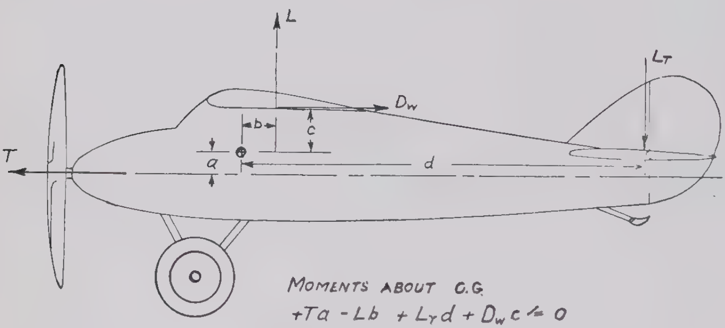
The equilibrium equation for lift then becomes

(a) $L_{wings} = W + L_{tail}$

The thrust T of the propeller must overcome the drag of the wings and the parasite drag or the drag of the rest of the wings.

(b) $T = D_w + D_p$.

Then taking moments about the center of gravity, assuming that a stalling or nosing up moment is positive, and denoting the arms of the various forces about the center of gravity by appropriate letters as shown in Fig. 58, we see that



FORCES ACTING ON A PLANE IN LEVEL FLIGHT

FIGURE 58

(1) the propeller thrust being below the center of gravity has a stalling moment, $+ Ta$.
(2) the lift on the wing has a diving moment—L_w b, about the center of gravity.
(3) the drag forces on the wing has a stalling moment $+ D_w$ c.
(4) the downward force on the tail has a stalling moment $+ L_t$ d.

(5) the resultant of the parasite drag is in this case probably below the center of gravity and therefore has a diving moment—D_p e.

The equation of moment equilibrium thus becomes

(c) $Ta - L_w\, b + D_w\, c + L_t\, d - D_p\, e = o.$

Example

(1) Our 1600 pound airplane of 200 square feet has a monoplane wing of aspect ratio 6. What is its chord? Let chord be c. Then the span is 6c, and $6c \times c = 6c^2 = 200$. Therefore $c = \sqrt{33.2} = 5.75$ feet.

(2) The center of gravity is placed at one-third of the wing chord from the leading edge and 1½ feet perpendicularly below the wing chord. The thrust line of the propeller is parellel to the wing chord and two feet below it. When the machine is flying steadily at 0 degree angle of incidence, what will be the moment of the propeller thrust about the center of gravity.

At 0° incidence $K_y = .00105$, and $K_x = .000051$. The parasite drag coefficient is .0000325 as before. Now $W = K_y\, AV^2$ so

$$V^2 = \frac{W}{K_y\, A} = \frac{1600}{.00105 \times 200} = 7620$$

and V = 87.2 miles per hour.

$$\begin{aligned} D_t &= (K_x + K_p)\, AV^2 \\ &= (.000051 + .0000325)\ 200 \times 7620 \\ &= 127 \text{ pounds.} \end{aligned}$$

The moment of the propeller thrust is ½ foot below the center of gravity, and it will have a stalling moment of $127 \times \frac{1}{2} =$ 63.5 foot pounds.

(3) If while flying in equilibrium at zero degrees, the engine is suddenly cut, will the machine have a tendency to stall or to nose down?

The propeller thrust was acting below the center of gravity and gave a stalling couple. When the engine is cut, this stalling moment disappears. The machine will have a tendency to nose down.

(4) What will be the moment about the center of gravity of the lift force?

At 0 degrees incidence, the center of pressure is at 45 per cent of the chord (see Chapter V). Therefore the center of pressure is at $5.75 \times .45 = 2.59$ feet from the leading edge, and .67 feet behind the center of gravity. Taking the lift as approximately equal to the weight of the machine, the lift exercises a diving moment of $.67 \times 1600 = 1070$ foot pounds about the center of gravity.

Problems

1. For the hypothetical plane of this article, calculate the angle of glide and the air speed for an incidence of 0, 2, 4, 6, 8, 10, 12 and 14 degrees.

2. Calculate the vertical speed in each case of the above problem. Is there apparently some gliding condition for which the vertical speed of descent is a minimum?

3. If you had to make a steep glide into a small field, would you prefer to come in at a small or at a large angle of incidence?

4. If the line of thrust of the propeller passes above the center of gravity of an airplane, and the engine suddenly fails, will there be a tendency to stall or to nose dive?

5. In the example given in this chapter, the distance from the center of gravity to the point at which the center of pressure of the horizontal tail surfaces may be supposed to act is 13 feet. When the machine is flying at 0 deg. incidence, what force in direction and magnitude will be required on the tail surfaces in order that there may be equilibrium?

6. If the plane we speak of is flying at 6 degrees incidence, what will be (a) the speed (b) the propeller thrust (c) the moment of the thrust about the center of gravity (d) the moment of the lift force about the center of gravity assuming that the lift is approximately equal to the weight.

Answers

PROBLEM 1

K_p = .0000325

Angle of Incidence	K_y	K_x	K_x+K_p	$\tan = \ominus \frac{K_x+K_p}{K_y}$	$\ominus$	$\cos\ominus$	m.p.h. V air speed
0	.00105	.000051	.0000835	.0785	4° 30′	.997	89.4
2	.00140	.000070	.0001025	.0732	4° 11′	.997	75.5
4	.00178	.000100	.0001325	.7045	4° 16′	.997	66.9
6	.00214	.000132	.0001645	.0769	4° 24′	.997	61.0
8	.00251	.000173	.0002055	.0819	4° 41′	.997	56.3
10	.00276	.000219	.0002515	.0912	5° 13′	.996	53.5
12	.00301	.000268	.0003015	.1001	5° 43′	.995	51.3
14	.00320	.000323	.0003555	.1111	6° 21′	.994	49.8

PROBLEM 2

Angle of Incidence	Angle of Glide $\ominus$	Sin $\ominus$	V sin = $\ominus$ (mph) V vertical
0	4° 30′	.0785	7.02
2	4° 11′	.0729	5.50
4	4° 16′	.0744	4.97
6	4° 24′	.0767	4.68
8	4° 41′	.0816	4.60
10	5° 13′	.0909	4.86
12	5° 43′	.0996	5.12
14	6° 21′	.1077	5.35

At 8° incidence the vertical velocity of descent is a minimum.

(3) In making a steep glide into a small field it is better to come in at a small angle of incidence. The landing speed will be a little higher but the ship will not have a tendency to

"zoom" when flattened out. This would happen if the coefficient of lift were large as in high incidence.

(4) If the center of gravity is below the thrust line there is present a diving moment in ordinary flight under power. When the engine cuts, this diving moment disappears since the thrust is now absent. The plane will now have a very marked tendency to nose up or stall.

(5) At 0° incidence c.p. is at 45% of wing chord or $.45 \times 5.75 = 2.59$ ft. from leading edge.

The c.g. is at 1.92 feet from L.E.

$2.59 - 1.92 = .67$ ft. (moment arm of lift force)

$L_w\, b = .67 \times 1600 = -107$

$T\, a = \frac{1}{2} \times 127 = 63.5$

$D_w\, c = 1\frac{1}{2} \times 77.6 = -116.4$

where $77.6 = D_w = .000051 \times 200 \times 7620$

The net moment is —159.9 ft. lbs. in a diving direction. Therefore a down load on the tail is needed to counteract this tendency. The magnitude of this force is:

$$\frac{159.9}{13} = 12.3 \text{ lbs.}$$

(6) $W = 1600\#$

$A = 200$ sq. ft.

$$\text{at } 6° \begin{cases} Ky = .00214 \\ Kx = .000132 \end{cases}$$

$$\text{(a) } V = \sqrt{\frac{W}{A\,Ky}} = \sqrt{\frac{1600}{200 \times .00214}} = 61 \text{ m.p.h.}$$

$D_t\ (.0000325 + .000132)\ (200) \times (61)^2 = 123$ lbs.

But $D = T$

Therefore moment of thrust about center of gravity is

$$\frac{1}{2} \times 123 = 61.5 \text{ ft. lbs.}$$

The center of pressure at 6° is exactly at $\frac{1}{3}$ of wing chord therefore the lift force having zero arm has zero moment.

CHAPTER VIII

ELEMENTS OF AIRPLANE MECHANICS (Continued)
TURNING THE CONTROL SURFACES

Centrifugal Force

Whenever a body moves in a circle, centrifugal force comes into play. A simple experiment to illustrate centrifugal force can be performed by taking a bottle of milk, open at the top,

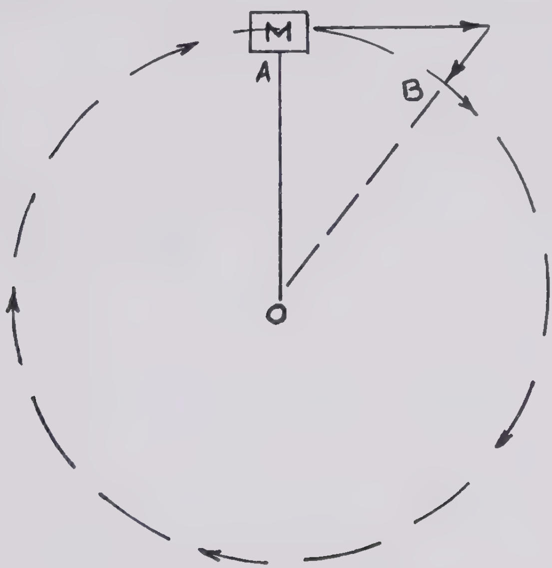


FIGURE 59

and tying a piece of string round the neck of the bottle. The bottle can then be swung round and round without a drop of milk being spilt. Centrifugal force acts on the milk outward

from the center of the turn and prevents it from flowing out at the open end.

It is somewhat harder to illustrate centrifugal force on a mathematical basis.

Newton stated that a body remains at rest or persists in a motion in a given direction unless acted on by some force.

Suppose that a body, M, as shown in Fig. 59, is moving in a circle with center O. When the body M is at the point A, its motion for the instant is in a direction perpendicular to the line OA. If it is to continue on the circle and go to point B, some force must be exercised on it, therefore, to change its direction of motion. This force, acting towards the center of the circle, is termed centripetal force and is equal and opposite to the centrifugal force. In the case of the bottle of milk, the centripetal force is provided by the pull in the string.

In going round a circle, there is evidently a continual change in the direction of motion, and reflection will show that there is really always a continual acceleration towards the center of the circle. It can be shown mathematically that this acceleration in feet per second, per second is equal to

$$\frac{v^2}{R}$$

where v is the tangential velocity along the circumference of the circle in feet per second, and R is the radius of the circle in feet.

Since force equals mass $\times$ acceleration, and mass $= \dfrac{\text{weight}}{g}$ the centrifugal force in pounds, acting on a weight of W pounds will be given by the expression

$$F = \frac{W}{g}\,\frac{v^2}{R}$$

Example

A bottle of milk weighing 3 pounds is swung round at the end of a 3 foot string at the rate of once a second. What is the pull in the string?

The circumference of the circle is $2\pi R = 2 \times 3.14 \times 3 =$ 18.84 feet. Therefore the tangential velocity is 18.84 feet per second. The centrifugal force

$$F = \frac{W}{g}\frac{v^2}{R} = \frac{3}{32.2} \times \frac{18.84^2}{3} = 11.03 \text{ pounds.}$$

It should be noted carefully that (a) the greater the tangential velocity, the greater the centrifugal force, (b) for a given tangential velocity, the centrifugal force will be larger for a smaller radius of turn.

A Force to Counteract Centrifugal Force Needed on Turns

Whenever a body moves in a circle, a centripetal force to counteract the centrifugal force is needed. When a man turns a corner on a bicycle, he bends his body and the bicycle inwards for this reason. On a circular automobile racing track, the track slopes inwards to its center. The explanation of the bank in making an airplane turn is based on the same principle.

Equilibrium of Forces on a Banked Turn

If a pilot tried to make a flat turn, that is without inclining or banking his machine, centrifugal force would make his machine sideslip or skid away from the center of the turn. When the machine is correctly banked as shown in Fig. 60, there is equilibrium of forces and the plane moves on the circumference of a huge circle, without skidding either in or out. As can be seen from the sketch, the wing tip nearest the center of the turn is inclined downwards. The lift of the wings is also inclined inwards, and counteracts not only the force of gravity but also the centrifugal force. If θ is the angle of bank, we can resolve the lift force into two components and get the following equations, where $v =$ speed in feet per second.

(I) $L \sin\theta = \text{Centrifugal force} = \frac{W}{g} \frac{v^2}{R}$

(II) $L \cos\theta = W$

Dividing the first equation by the second, we get

(III) $\tan\theta = \frac{v^2}{gR}$

A number of interesting conclusions emerge from the diagram of Fig. 60 and from these equations.

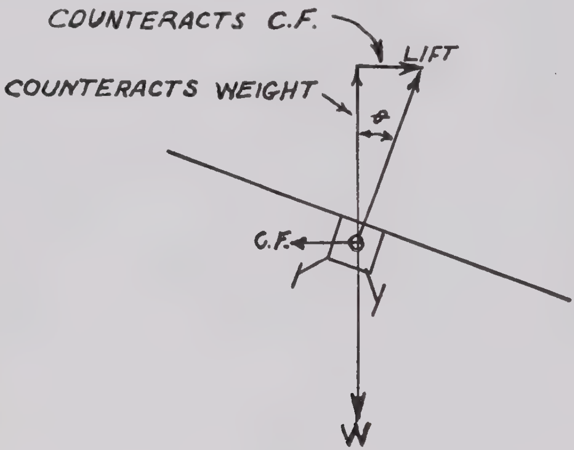


FIGURE 60

The lift of the wings in a turn must be greater than the weight of the plane.

The steeper the angle of bank the greater is the lift.

The steeper the angle of bank, the greater is the value of $\frac{v^2}{gR}$ and the greater the centrifugal force $\frac{Wv^2}{gR}$.

For a given angle of bank, $\frac{v^2}{gR}$ always has the same value,

and the centrifugal force has the same value. We can however make v^2 large, and R large, or make v^2 small and R small.

This means that at any angle of bank, the pilot can fly fast but on a large radius, or fly slowly and on a small radius.

We can add another convenient equation:

Since $L \cos\theta = W$, therefore

$$\text{(IV)}\ L = \frac{W}{\cos\theta} = K_y\ A\ V^2.$$

It follows from this that on a turn, at a given speed, since the lift is greater than the weight, the lift coefficient must be greater than in straightway flight. In other words on a turn at a given speed, the angle of incidence must be greater than in straightway flight.

A few examples will make our ideas clearer:

Examples

(a) A plane of 1600 pounds gross weight is turning at 100 miles per hour, with an angle of bank of 45 degrees. What is the centrifugal force? The lift of the wings? The radius of the turn?

Since the plane is banked at 45 degrees, the weight is equal to the centrifugal force, which is therefore 1600 pounds. The lift is the resultant of the weight and centrifugal force $= \sqrt{1600^2 + 1600^2} = 2260$ pounds. The speed is 146.7 feet per second and $\tan 45° = 1$ therefore $1 = \frac{v^2}{gR} = \frac{(146.7)^2}{32.2 \times R}$ and the radius of the turn is 667 feet, approximately.

(b) If this machine of 1600 pounds is provided with a Clark Y wing of 200 square feet, what will be the angle of incidence in straight away flight at 90 miles an hour and on a bank of 30 degrees at 90 miles an hour?

In straight flight $W = K_y AV^2$ and $K_y = \frac{W}{AV^2} = \frac{1600}{200 \times 90^2} = .00099$. From the curves and tables for Clark Y in Chapter 5, we see that this corresponds to an angle of incidence of $-0.25°$.

On the 30° bank, $L = \frac{W}{\cos} = \frac{W}{\cos 30°} = \frac{1600}{.8660} = 1850$ pounds.

Hence $K_y = \frac{L}{A\,V^2} = \frac{1850}{200 \times 90^2} = 0.001142$.

From the Clark Y curves of Chapter 5, we see that the angle of incidence must be a little over $-\frac{1}{2}$ degrees, or considerably more than on the straightaway.

Why a Pilot May Lose Consciousness on a Very Fast, Steep Bank

In the Pulitzer Cup races, where pilots made very fast steep turns, they would lose consciousness for brief intervals of time.

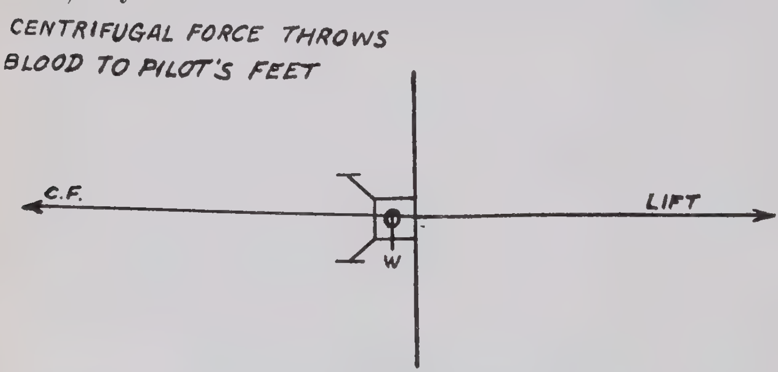


FIGURE 61

This is explained by the diagram of Fig. 61. The centrifugal force in such turns became very great, and the pilot's body

would assume an almost horizontal position. The centrifugal force would act on the blood in his brain and tend to force it in the direction of his feet. When the blood was forced from his brain he became unconscious; and it was only after the plane had straightened out and the blood returned to his brain that he regained consciousness.

The Lateral Inclinometer on a Bank

To show the pilot whether his plane is on a level keel or not, a lateral inclinometer is employed, which in its simplest form is a curved glass tube, filled with colored alcohol, with an air bubble which is at the center of the tube when the plane is level. This instrument is shown in Figure 62. When the plane

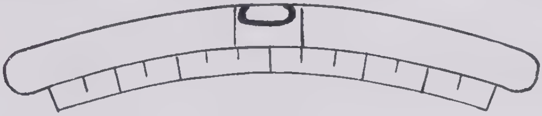


FIGURE 62

rolls sidewise, the air bubble travels in the direction of the high wing tip and by means of a graduated scale indicates the degree of bank. On a turn the air bubble is subjected to both gravity and centrifugal force and if the turn is correctly executed, the bubble remains in the exact center of the tube.

Incorrect Banking

If on a turn, the pilot banks the plane too much, it will sideslip towards the center of the turn. If the plane is underbanked, it will skid out away from the center of the turn. This is illustrated in Figure 63. The inclinometer bubble, central in a correct bank, will move out as the airplane sideslips towards the center of the turn, and conversely move in as the plane skids out.

More Speed and Power on a Turn

We have seen that a turn can be made at the same speed as in rectilinear or straightaway flight but at a higher angle of

incidence, so as to give the greater lift required on the turn. If a turn is made at the same angle of incidence as in rectilinear flight, then the speed must be increased to give the extra lift.

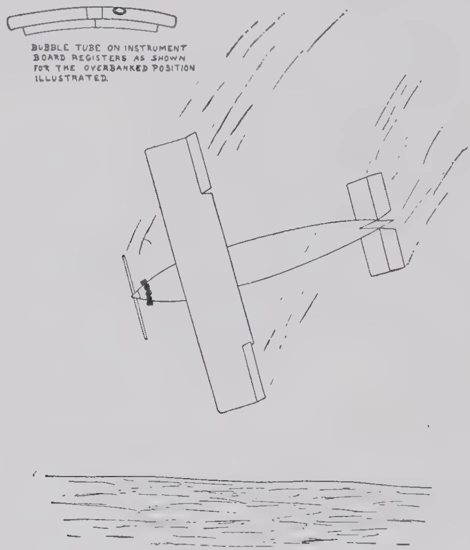


FIGURE 63

In either case, same speed or same incidence, the power on the turn must be greater.

The power required for the wing is $\dfrac{K_xAV^3}{375}$ (see Chapter VI).

At the same speed, but at a higher angle of incidence on the turn, the K_x and the power required are likely to be greater.

At the same angle of incidence but at a higher speed on the turn the power will be greater because it varies as V^3.

We can now answer the question as to how the pilot can act so as to make a turn without losing altitude. If he is flying at maximum speed, full throttle, he evidently has no reserve of power to make a turn at the same speed. Therefore he has

to nose the machine up a little so as to increase the angle of incidence and fly at less than top speed on the turn.

If the pilot is flying in a straight line, with the engine somewhat throttled, then he has two alternatives in making a turn. One is to make the turn at the same angle of incidence, but greater speed, in which case he has to open up his engine. The other alternative is again to raise the nose slightly and make the turn at lower speed.

It is of course possible to make a turn at the maximum speed of the airplane and even beyond this speed. But in that case gravity has to supplement the power of the engine and height has to be lost on the turn.

Example

The plane of 1,600 pounds, for which performance calculations were made in Chapter VI, Problem No. 5, needed 31.8 horse-power in rectilinear flight at 90 miles per hour. If a banked turn of 30 degrees is made at the same angle of incidence as in straight flight, what is the speed and what is the power required? The lift $L = \frac{W}{\cos\theta} = \frac{1600}{\cos 30°} = \frac{1600}{.866} = 1850.$

In straight flight $1600 = K_yAV_1^2 = K_yA(90)^2$; on the turn $1850 = K_yA(V_2)^2$; hence $\frac{1600}{1850} = \frac{90^2}{V_2^2}$ and the speed on the turn works out 97 miles per hour. At the same angle of incidence, the power varies as the cube of the speed. Therefore, power required on the turn equals $\frac{31.8 \times (97)^3}{(90)^3} = 39.7$ horse-power for Wing alone.

Learning to Make a Turn

After a student has learned to fly straight and on an even keel, the next thing to learn is how to make a correct turn. A

turn may require the application of rudder, ailerons and elevator and is one of the most difficult as well as one of the most essential maneuvers to learn. It seems necessary at this stage to study the properties of the control surfaces.

The Control Surfaces

The control of an airplane appears to be so instinctive a matter that we have apparently taken for granted hitherto the functions and properties of the control surfaces.

The easiest way to understand the maneuvers of the airplane is to imagine that it has three axes at right angles to one another, and meeting at the center of gravity. These three

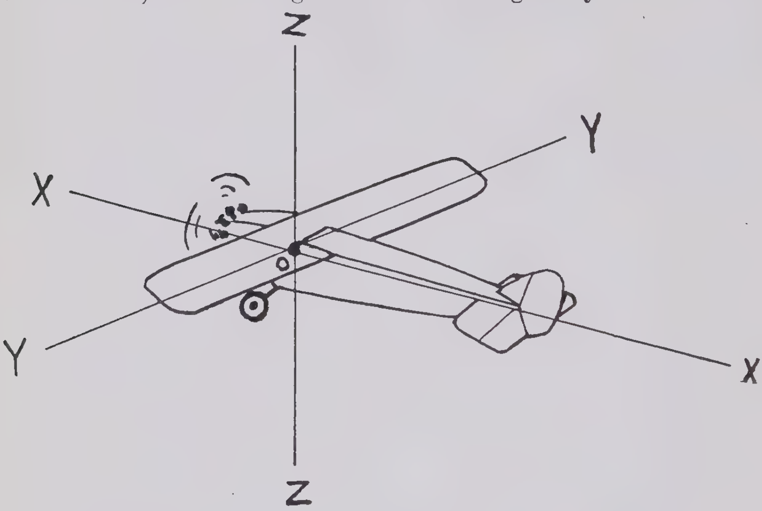


FIGURE 64

axes are shown in Figure 64. There is the longitudinal axis which runs the length of the airplane. It is marked XX in the diagram. At right angles to this there is the transverse or lateral axis YY. Then there is the vertical or normal axis, ZZ.

These axes are considered fixed in the airplane, and move with it in space.

The Wright Brothers realized the necessity of having independent control about the three axes of the airplane and achieved such control.

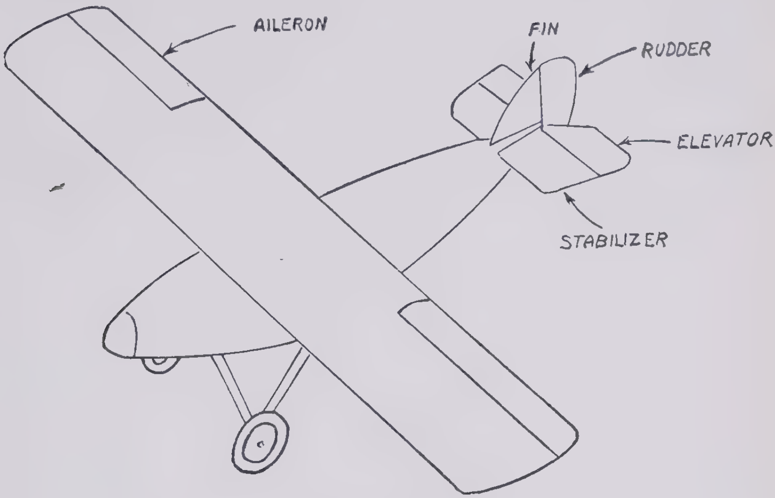


FIGURE 65

The first control is the elevator which noses the plane down or up, or pitches it about the transverse or lateral axis YY.

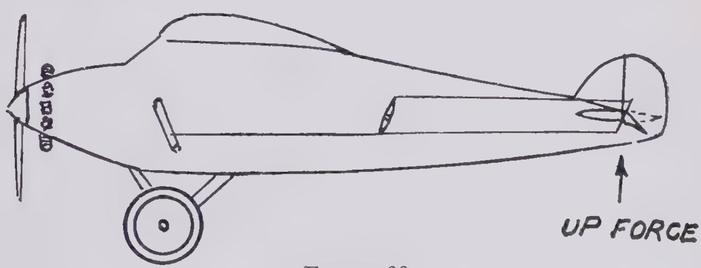


FIGURE 66

The elevator is hinged in back of the stabilizer (whose properties we shall study later) as shown in Figure 65. When the

elevator is turned up, the air strikes it from above; there is a downward force on the elevator and the nose of the airplane rises. When the elevator is turned down, the air strikes it from below; the force on the elevator is from below and the nose of the plane is depressed. To actuate the elevator, the control stick is moved back and forth. Pushing forward on the stick,

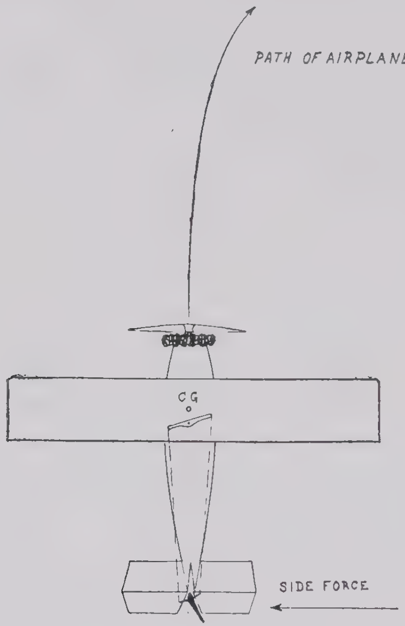


FIGURE 67

as can be easily gathered from Figure 66, turns the elevator down and depresses the nose—a perfectly instinctive maneuver. Pulling the stick back raises the nose of the plane.

The action of the rudder and rudder bar is illustrated in Figure 67. Pushing the right foot forward turns the rudder to the right. The air strikes it on the right side and the plane turns to the right. Giving right rudder means starting a turn

to the right therefore. The rudder evidently controls the airplane about the vertical or normal axis ZZ.

The ailerons are hinged in back of the wing, toward its end. The ailerons are actuated by the control stick, and as can be seen from Figure 68, the connecting system between the stick and the ailerons is such that when the stick is pushed to the right, the right aileron is turned up, the left aileron is turned down. The right aileron experiences a force from above, the left aileron a greater force from below. Accordingly the air-

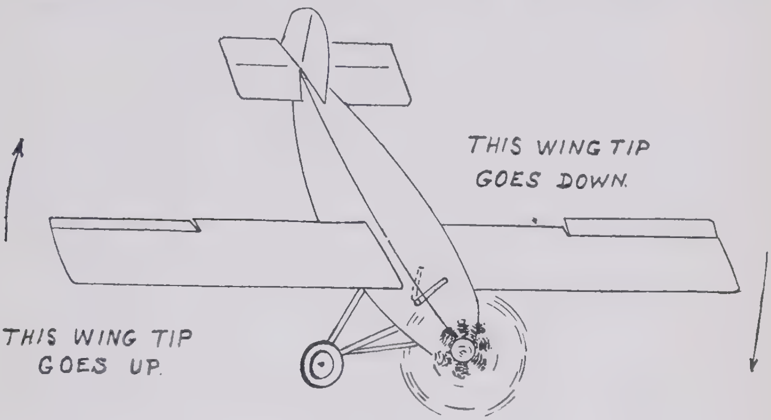


FIGURE 68

plane rolls down on the right side. The ailerons control the movement of the airplane about the longitudinal axis XX.

Turning about the transverse axis YY is termed pitching.

Turning about the longitudinal axis XX is termed rolling.

Turning about the vertical axis ZZ is termed yawing.

When the airplane is banked steeply, the functions of the controls apparently get confused: the rudder may raise or depress the nose relative to the earth's horizon, the elevator may be turning the plane in a circle. The so-called inversion of the controls is only apparent. The action of the controls about the three axes of the airplane always remains the same.

It is very important to remember this when considering the maneuvers of airplane and the functioning of the controls in the various positions of the airplane.

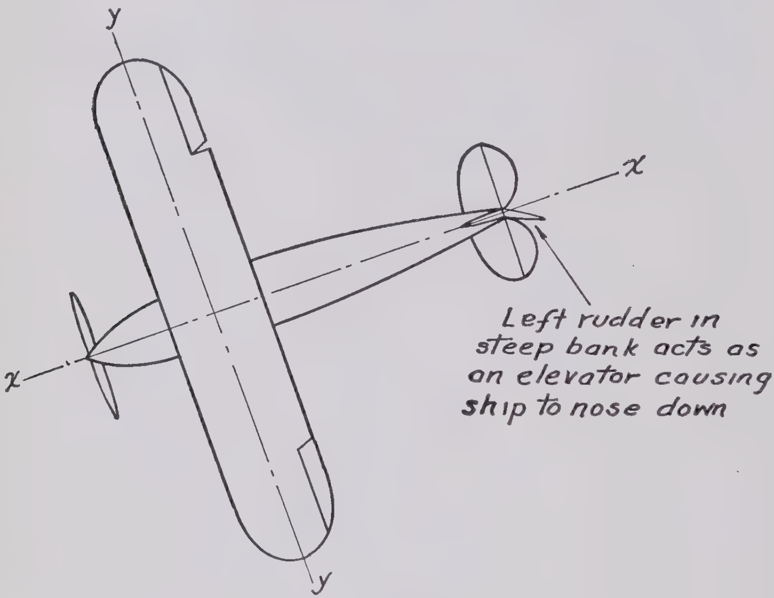


FIGURE 69

Problems

1. A pilot banks his plane, weighing 2,100 pounds, at a speed of 100 miles an hour. The angle of bank is 60 degrees.
   a. What is the centrifugal force exerted on the plane?
   b. What is the lift on the wings?
   c. What is the radius of turn?
   d. What is the angle of attack if the wing section is a Clark Y, and the wing area 300 square feet?
   e. What would be the speed of the plane in straightaway flight at same angle of attack?

f. What would be the angle of attack if the speed on straightaway were 100 miles an hour as on the turn?
g. What is the power required for the wing on the turn and on straightaway flight at 100 miles?

2. A plane is cruising at 80 miles an hour, when the pilot pushes the stick to the right. What happens if the speed of the plane remains the same?

3. The pilot pushes the left end of the rudder bar forward; all other controls neutral. What happens?

Answers

1. a. 3,640 lbs.
   b. 4,200 lbs.
   c. 385 feet
   d. 2 degrees
   e. 70.7 miles per hour
   f. –1¾ degrees
   g. 56 horsepower
   35 horsepower

2. As the pilot moves the stick to the right, he depresses the left aileron and raises the right aileron; therefore, there is more lift on the left wing than on the right. The right wing drops, and the plane makes a right bank. Since the speed in the bank is the same as in level flight, the nose of the plane drops a little.

3. As the left end of the rudder bar moves forward, the nose of the plane moves toward the left, since the rudder is deflected and the force on it moves the tail of the plane toward the right. If the rudder is moved suddenly or deflected very much while the plane is in level flight the plane will "skid" since there is no horizontal component of the lift to counteract or work against the centrifugal force. See Figure 60 for the forces acting on a plane in a bank.

CHAPTER IX

ELEMENTS OF AIRPLANE MECHANICS (Continued)
TURNING

Yawing Tendency of the Ailerons

There is one important property of the ailerons which has a bearing on the correct turn and that is the yawing moment of the ailerons.

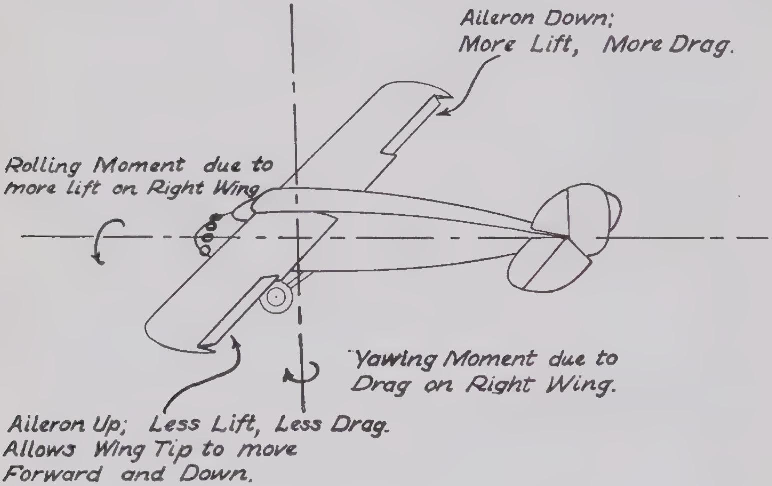


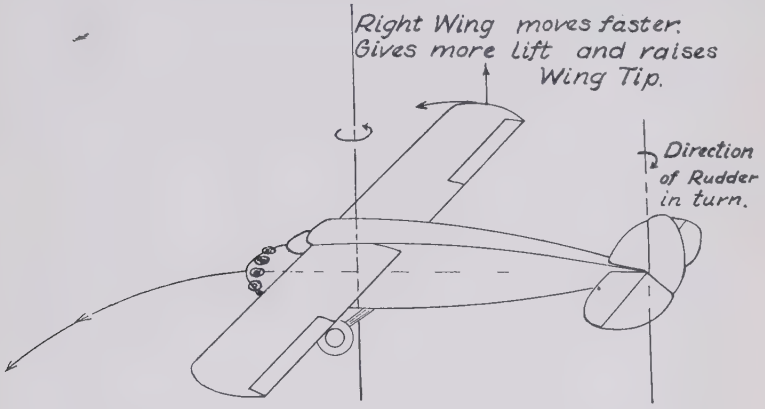
FIGURE 70

If the right aileron is depressed, and the left aileron is raised, there is more lift on the right side and at the same time more drag. (This would seem to be axiomatic on the ground that where there is more lift there is also more drag, but a sounder explanation will be given in a later chapter.) Hence, if a machine is banked to the left by means of the ailerons, there

will be a simultaneous tendency to turn the machine to the right. This is illustrated by the diagram of Figure 70.

Natural Banking Moment

If a plane is turning about some center, no matter how distant, then as is shown in Figure 71, the tip which is further away from the center of the turn is moving more rapidly than



PLANE IN LEFT TURN

FIGURE 71

the inner tip. Therefore the outer tip has more lift than the inner tip of the wing, and the plane has what is known as a natural banking moment.

Starting a Turn and Staying in a Turn

We are now in a better position to discuss the whole maneuver of the turn.

Suppose the plane is flying straight and level. As stated in the previous chapter, there are two alternatives involved in making the turn: one is to turn at the same angle of incidence, but greater speed in which case the engine has to be opened

up; the other is to increase the angle of incidence slightly and make the turn at a lower speed without opening out the engine.

Suppose we remember this rule and wish to make a turn to the left. To turn the machine to the left, left rudder is applied. If the rudder alone were applied, then centrifugal force would make the plane skid to the right. Therefore ailerons must be used to bank the plane with left wing tip lower than the right.

For anything but the very gentlest turn, sufficient rudder must be applied in order to start the turn, but also to overcome the adverse yawing tendency of the ailerons.

Suppose that when the turn is started, the stick were held at its original sidewise displacement and the ailerons in their original displaced position accordingly. Then the "natural" banking moment of the machine would come into play, and the plane would over bank.

Therefore as soon as the turn is well started, the ailerons should be eased off.

But if the ailerons are eased off, their "adverse" yawing moment disappears. Hence the rudder must be eased off likewise.

It might be thought that once a steady turn is reached, the rudder can be straightened out completely. This is not the case, because the plane always opposes turning. The outer wing tip turning faster than the inner wing tip has not only more lift but also more drag. The fuselage, the vertical fin, every exposed part of the airplane, continues to oppose the turn. Therefore throughout the turn steady pressure has to be applied to the rudder bar.

It is probable also that the ailerons will have to be displaced slightly for some planes in a direction opposite to the original displacement so as to counteract the "natural" bank of the wings.

Let us see next whether the elevator has any part to play in the turn.

We stated that if on the turn, the engine is not let out, the angle of incidence must be increased and the air speed decreased. This can be accomplished by pulling back on the

stick. But the stick must not be pulled back too violently before the turn is started—otherwise the plane will begin to climb, or there may even result a loop somewhere between the vertical and the horizontal.

Again the rudder always turns the plane about the normal axis of the plane. In level flight, this axis is vertical. In turning the plane is banked, and this axis is inclined sidewise. Hence the rudder tends to turn the nose of the plane downward as illustrated by Figure 72. If the turn is to be performed in

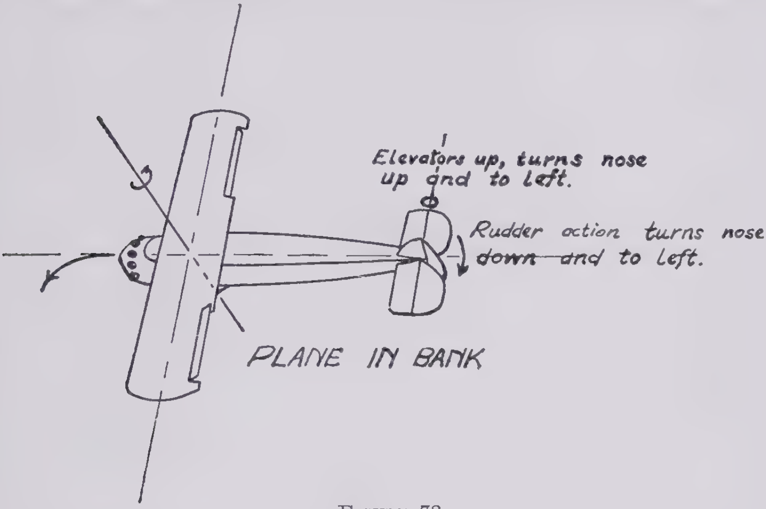


FIGURE 72

a horizontal plane, this tendency of the nose to drop must be resisted by a slight backward pull on the elevator.

The backward pull on the stick must not be too great, or else there will be a disposition to a climbing turn. It is not certain that the machine will have sufficient power for a climbing turn. Certainly the beginner should not attempt a climbing turn, or a stall and a subsequent spin may follow. Any tendency of the nose to rise above the horizon should be checked therefore by easing the stick forward.

We can easily explain the process of coming out of the turn. To remove the bank, we must apply left aileron. This introduces again the adverse yawing moment which tries to continue the turn. Therefore simultaneously with the left aileron, sufficient right rudder must be applied. Also the stick must be pushed forward, because right rudder on a left bank causes the nose to rise. When the wings are level, the ailerons are neutralized and rudder is brought back to normal.

Simple Rules for the Turn

We have tried to make this explanation of turning as simple as possible. It may nevertheless be puzzling. The arm chair aviator has plenty of time to explain any maneuver. The practical flier should understand the underlying principles of a maneuver if possible, but he should also have simple rules at his command, memorized in ground school, practised in the air, until their application becomes instinctive.

Such rules are given in the manuals of the Army and Navy, and in the excellent pamphlets issued by private schools. They read somewhat as follows below. It will be an excellent exercise for the reader to check the correctness of these rules in the light of our theoretical discussion:

1. To make a left turn, apply left bank and ample left rudder together.
2. If engine is not let out, when turn is begun, pull stick back gently.
3. When desired bank is reached, ease off ailerons and rudder.
4. Keep nose level throughout the turn. To make horizontal turn, use both rudder and elevator.
5. Maintain same degree of bank and constant pressure on rudder throughout the turn.
6. To come out of the turn, apply right aileron and right rudder.
7. When wings are level, neutralize ailerons, then put rudder in normal position.

Slips and Skids

A sideslip is generally defined as a movement of the plane towards the depressed wing tip and occurs of course when the centrifugal force is not large enough for the bank. A practical warning of the sideslip is wind blowing from the inner or lower side of the plane on the face. Sideslip can be readily eliminated by using a little more rudder.

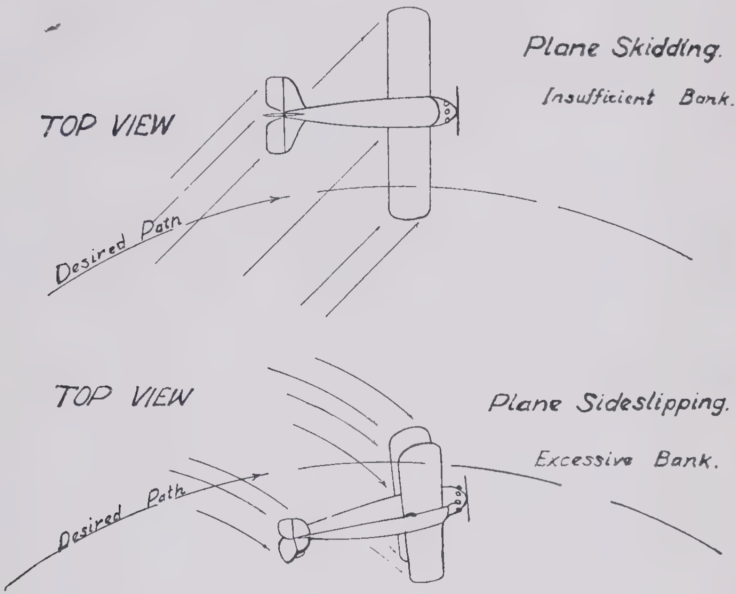


FIGURE 73

A skid occurs when the lift in the bank is insufficient to balance the centrifugal force, and the warning signal is a wind from the outer or high side of the face. Easing the pressure on the rudder is the obvious remedy; the alternative is to increase the bank.

The side-slip and skid are illustrated in Figure 73.

Engine Torque Effects

Action and reaction are equal and opposite. Therefore if the engine applies a torque to the propeller which it is turning, then the engine must be tending to turn the airplane in the opposite direction to the rotation of the propeller. The readiest way to counteract this turning moment is by changing the rig-

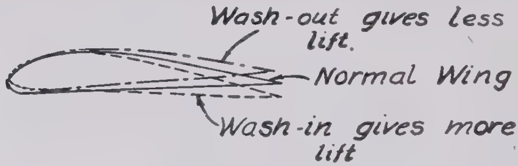


FIGURE 74

ging of the wings so that there is more lift on one wing tip than on the other. Thus with a right hand propeller there is a tendency to bank the plane to the left. Therefore the incidence on the left wing tip should be increased, or "washed in." Another plan is to decrease the incidence on the light tip. or use "wash out" or the left wing tip may be slightly

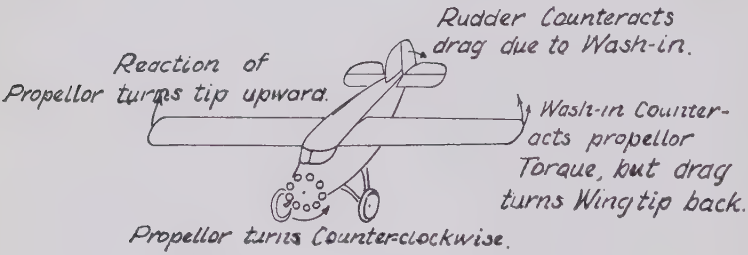


FIGURE 75

"washed in" and the right wing may be slightly "washed out." This change in rigging is easily made in a biplane by adjustment of the lift wires, preferably in combination with adjustable interplane struts. "Wash in" is illustrated diagramatically in Figure 74.

We have seen that where there is more lift, there is also more drag. If, therefore, the torque of the right-hand engine is eliminated by change in the rigging so as to give more lift on the left wing tip, there will also be more drag on the left wing tip. A certain amount of right rudder always has to be employed therefore. Sometimes a rubber shock absorber cord is attached to the rudder bar to relieve the pilot on a long flight. The combined effect of wash in, wash out and rudder is illustrated in Figure 75.

Apparent Changes of Control Action in Steep Banks

People often speak of "inversion of the controls" in steep banks. The controls never change their functions however steep the bank may be. The elevators will always pitch the plane about the transverse or lateral axis, the rudder will always turn the machine about the normal axis of the plane, the ailerons will always roll the plane about the longitudinal axis. But when the machine is banked steeply, then these axes of the plane no longer have their normal attitude relative to the earth. The controls will continue to function about their respective axes just as they always do, but their effect as regards the movement relative to the earth or the horizon will be different.

Suppose we consider the case of an almost vertical bank, shown in Figure 76. This can only be made on a very powerful and very fast machine, since only a small proportion of the lift is now counteracting the force of gravity. (It is the author's guess that in an almost vertical bank, lateral forces on fuselage and wings also contribute in carrying the weight of the plane.) It can be seen from this diagram that the transverse axis about which the elevator acts is now vertical. Therefore it is the elevator which is now turning the plane in the horizontal plane about the vertical axis in space. On the other hand the normal axis about which the rudder acts is now horizontal. Therefore it is the rudder which is dipping or raising the nose of the plane. The longitudinal axis on the

other hand remains horizontal and therefore the ailerons behave as they always do, acting in roll.

If the bank has any value between 0 degrees and 90 degrees, then the rudder is partially turning the plane about a truly vertical axis, partially pitching it the nose up or down about

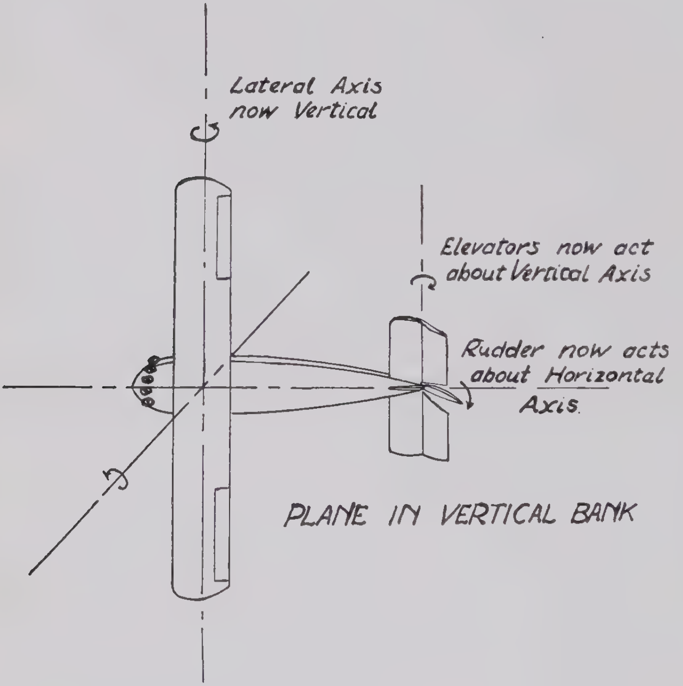


Figure 76

a horizontal axis in space. In the same way the elevator will partially help to turn the plane about a vertical axis in space, partially pitch it about a horizontal axis in space.

The reader will find it a pleasurable exercise in imagination to visualize the preceding paragraph.

Problems

1. If the rate of turn is too slow for the angle of bank, what will the airplane do? What should then be done with control stick and rudder?

2. If the rate of turn is too fast for the angle of bank, what will the airplane do? What should then be done with control stick and rudder?

3. If the rudder is put on before the airplane begins to bank, what will happen? What is the remedy?

4. If too much elevator is applied at the beginning of the turn, what is likely to happen?

5. If too much rudder is applied after the turn has developed, what will happen?

6. If too little elevator is used after the turn has developed, what will happen? What is the remedy?

7. If there is too much elevator what will happen?

8. Explain the following extract from the British Flying Training Manual:

"In order to come out of a turn, considerable effort is required for sufficient application of the ailerons when taking off the bank. Full opposite aileron should be firmly applied, otherwise the 'aeroplane' will be slow to respond. If top rudder is put on too soon, the 'aeroplane' side-slips; if it is put on too late, it is slow in coming out of the turn and the pilot will be not facing the point of horizon at which he was aiming. Failing to centralize the rudder at the correct time will cause the 'aeroplane' to skid."

9. What will happen if the wing is not checked when the proper bank is reached?

10. The student feels a considerable slip. Should he discontinue the turn and if so, how? What may be the effects of a serious skid?

11. Should ailerons be used on a very steep, steady turn?

12. The British Flying Training Manual gives the following instructions for a steep turn.

(I) Commence as for an ordinary wide turn, but the bank must be increased by firm application of the aileron control.

(II) A little rudder should be first applied towards the direction of the turn, but as the bank increases the rudder must be adjusted to keep the nose on the horizon.

(III) At the commencement of the turn, the elevator should be used to keep the nose from falling, but as the bank increases the control column should be pulled further and further back to keep the "aeroplane" turning in the horizontal plane.

Comment on these instructions.

Answers

1. If the rate of turn is too slow for the angle of bank, the plane will sideslip towards the depressed wing, because there is not enough centrifugal force to balance. The remedy is to give more rudder (which is sometimes termed giving bottom rudder). If the bank is steep, the rudder may then act in such a fashion as to depress the nose. Therefore it may also be necessary to pull the stick back a trifle.

2. If the rate of turn is too fast, the plane will skid out. Bottom rudder should be eased off. If the bank is steep, then the same effect may be obtained by easing the control column forward.

3. If the rudder is put on before the airplane begins to bank, the plane will skid out. The remedy is to reduce the amount of rudder or increase the bank.

4. If the stick is pulled too far back at the beginning of the turn, there may ensue a climbing turn which is not advisable for a beginner, nor on any but powerful machines. Or the machine may do a loop about some axis between the vertical and the horizontal.

5. Too much rudder after the turn has developed will cause a skid outwards and the machine will be at an angle to its flight path.

6. If too little elevator is used after the turn has developed, particularly if the turn is a steep one, the airplane will slip inwards (because the elevator has practically the property of

a rudder). The remedy is more elevator to hasten the turn or less bank.

7. If too much elevator is used for steep turning, while at the same time there is not enough bottom rudder to keep the nose up, the nose will drop and the airplane will ultimately spin.

8. Answer is left out, as a special problem for the reader.

9. When the proper bank is reached, the wing supplies a "natural" banking moment. Hence if wing is not checked by the ailerons, an overbank will result leading to a tight spiral or a spin.

10. If the slip is considerable, it is safer to discontinue the turn. If slipping is towards the left, right rudder and left aileron should be used for a short time. At the same time the nose is dropped to ensure adequate speed. After the neutralizing process the plane will be on a course to the right of that before the slip.

11. Ailerons are not needed on a steep, steady turn since both wing tips are then moving with approximately the same speed, and there is no "natural" banking moment.

12. The answer is left out, as a special problem to the student.

CHAPTER X

LANDING AND LANDING RUN

Bouncing on a Landing

In Chapter 7, we have already discussed the problem of coming into a small field, either by recovery from a steep dive or by a stalled glide. A normal landing into a field of small dimensions depends on the same principles, which it is interesting to discuss a little more in detail.

Suppose the pilot is flying the hypothetical machine of Chapter 7, and gliding at 6 degrees incidence, 4° 24′ to the horizontal and at a speed of 61 miles per hour. The glide path is very flat as indicated by the sketch of Figure 78.

Suppose that the plane has very powerful elevator control, and is short-coupled, having all its weights bunched close together about the center of gravity. Suppose that just before landing, the pilot pulls back very hard on the stick. Such a plane will respond very quickly to the controls, and the angle of incidence to the glide path will be rapidly increased without much loss in speed. Let us suppose further that the machine is brought to the angle of incidence corresponding to maximum lift without *any* loss of speed.

The area of our hypothetical machine was 200 square feet, the wing section was Clark Y, the weight 1,600 pounds. The maximum Ky at 14 degrees incidence for this wing is .0033. The lift at 61 m. p. h. and this Ky will be

$$.0033 \times 200 \times 61^2 = 2460 \text{ pounds}$$

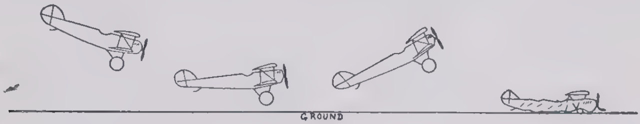
or some 54.5% more than the total weight of the plane.

If the lift is greater than the weight, the machine will evidently ascend, or "bounce" in flying vernacular.

Of course no plane is maneuverable enough to change its flight attitude instantaneously. But too rapid a flattening out

process just near the ground always leads the student into difficulties.

After the "bounce" the plane will probably "stall" a few feet from the ground, then drop and hit the ground with some degree of shock, a process called "pancaking." See Figure 77.



SUDDEN STALLING AND "PANCAKING"
FIGURE 77

Sometimes after the "bounce" there may be enough speed left to nose the plane down again and then make a second and better landing. Or, if the engine is running, it may be better to "give her the gun," that is, open up the throttle and fly off to attempt a second landing subsequently.

A Perfect Three Point Landing

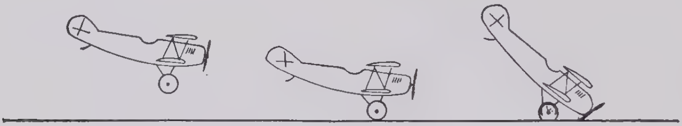
There is nothing which attracts so much admiration as a perfect three point landing. The pilot making such a landing continues his normal glide until the wheels are about 10 feet off the ground. (It requires much practice to gauge this height.) Then he will pull back gently on the stick, flattening

THREE POINT LANDING
FIGURE 78

out the path, increasing the angle of incidence and losing speed gradually, until the plane is "stalled" at about 2 feet above the ground. He will then be flying almost parallel to the ground and the front wheels and the tail skid will touch the ground at the same instant, without any perceptible shock. The process is illustrated in Figure 78.

The student may flatten out gradually, but misjudge his distance and stall several feet above the ground. He will then pancake badly and perhaps damage the undercarriage.

Not flattening out in time is perhaps a worse fault. The plane is then landing nose slightly down, and as the wheels strike the ground, there is a tendency to nose over as illustrated in Figure 79.



TAIL HIGH LANDING— NOSE OVER

FIGURE 79

The Advantage of Slow Landing

The advantages of slow landing are obvious. The kinetic energy as we know varies as V^2. Therefore a plane landing slowly has less kinetic energy to be destroyed by air drag and ground friction and the length of roll will be less. If an obstacle strikes the front wheels the dangers of damage to the undercarriage and of turning over are far less.

Since landing speed $V = \sqrt{\dfrac{W}{K_{y\ max.}\ A}}$.

that machine will have the slowest landing speed, which has

(1) the lowest loading in pounds per square foot of wing area, $\dfrac{W}{A}$

(2) the highest value of Ky max for the wing.

Commercial airplanes of today run rather high in loadings per square foot, with values going up as high as 14 pounds per square foot for large machines, and values well over 10 pounds per square foot for single engined cabin planes. This

is because low loading per square foot means a relatively large wing area and low maximum speeds. Since speed is the very essence of airplane utility, extremely low wing loadings cannot be tolerated.

There is not much to be gained either from using wings of high maximum Ky. The range for practicable airfoils is narrow, say .003 to .0036 for Ky max. There are heavily cambered wings which have values even higher than this, but they are very inefficient at high speed, or cruising.

One of the real problems of modern airplane design is to keep increasing the top speed while maining the landing speed within reasonable limits. Perhaps two or three thousand airfoils have already been designed and tested and there is not much further progress in the wing alone to be expected. Designers will be forced to employ sooner or later lift increasing devices such as the Handley Page slot, flaps at the rear of the wing, etc., which we will discuss in a later chapter.

Misleading Advertising of Landing Speeds

It is quite difficult to measure landing speeds exactly. Mechanical methods have been tried in which by means of electrical contacts and a revolving recording drum, the number of revolutions of the wheel from the instant of touching the ground to the instant when the wheels cease revolving were registered. These methods are somewhat complicated, and also take no account of the effect of wind. The usual combination of pilot tube and airspeed indicator is very unreliable at landing because the air flow is disturbed by the wing at high incidence, and possibly by the proximity of the ground. Also it is difficult to get an instantaneous reading and to be quite sure that this reading coincides with the instant of landing. The only definite measurement that can be made reliably is that of the minimum speed on the glide, which can be made by suspending a pitot bomb some forty feet below the airplane as shown in Figure 80. Suspended in this manner the pitot is free of interferences and gives reliable readings.

Owing to this difficulty in measuring landing speeds, and due

to the natural desire of manufacturers to have as low a landing speed as possible, advertisements of landing speed are often somewhat misleading. It should also be noted that in the

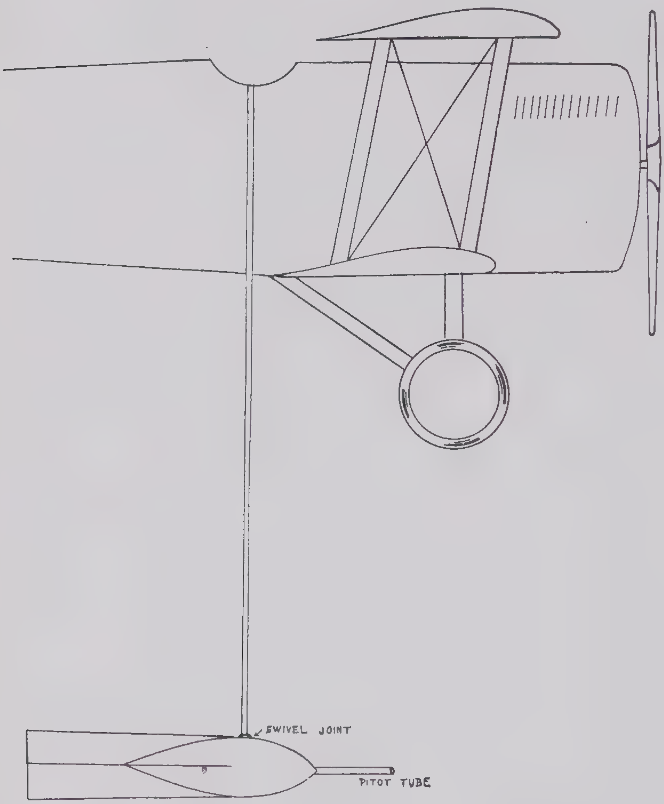


FIGURE 80

hands of a highly skilled pilot, and in a plane equipped with a good landing gear, the landing speed can be made to appear lower than it legitimately should be. The pilot who really

knows his craft can stall the machine three or four feet above the ground, bring the wing above the maximum lift coefficient where its drag is so large as to kill the speed, then land with the tail skid touching an instant or so before the wheels. Such a landing puts an undesirable strain on the plane, but will help to give the impression of a slow landing, and a short landing run.

Landing Fast

We have been emphasizing the value of slow landings as likely to minimize the shock, and as certain to shorten the landing run. Yet there are conditions when a pilot will prefer to make a fast landing with the propeller axis almost horizontal, then bringing the tail down gradually until the skid touches the ground. He will prefer to come in fast when the air is so gusty that it is hard to keep the plane on an even keel. Coming in fast, however, gives rise to the danger of "overshooting" unless there is a strong headwind. Also unless the field is very smooth there may be severe bouncing in the fast landing.

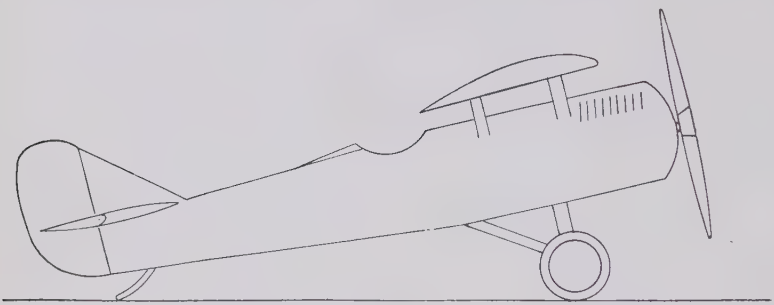
Factors Entering into Length of Landing Run

The mathematical expression for the length of the landing run is too complicated in expression and derivation to be discussed in these introductory articles.

The length of run increases with the square of the landing speed, because the kinetic energy of the plane varies as the square of the speed. Therefore, a plane lightly loaded per square foot of wing area should come to rest quickly. It is a fallacy to say that a large machine needs more space for its run than a small machine. They need the same length of run if they carry the same wing loading. It just happens that with smaller airplanes, designers use lower wing loadings as a rule. This is because small airplanes of the sport type may be required by their owners to alight in any restricted field, whereas the large transport planes operate only from large airports,

and are less liable to emergency landings because they are equipped with three engines.

Another important factor in the length of landing run is the L/D of the plane in its three-point landing attitude. At the instant of landing it is advisable to have the wing at its angle of maximum lift, so as to give the slowest possible speed. In the practical design of the airplane, it is therefore important to have the chassis of such length that the wing is indeed at a high angle when the airplane is in the three point attitude as shown in Figure 81. If this angle can be made a



AIRPLANE AT THREE POINT ATTITUDE

FIGURE 81

little bigger still than in the landing run, the wing will be very inefficient aerodynamically and will serve as an air brake.

Of course the ground friction affects the length of run. But the maximum ground friction ever found is only one-tenth of the weight of the airplane and is not as important a factor as might be imagined.

Many suggestions have been made by inventors and designers for air brakes, in the form of flaps hinged at the sides of the fuselages, etc. It may be safely said that such air brakes are likely to be clumsy and ineffective, and that wheel brakes which lock the wheels on landing are far better and more powerful in action than the braking action of the wing itself.

Machines of the future provided with lift increasing devices

and with wheel brakes may be expected to come to rest in about 100 feet or even less.

How Brakes Affect the Design of an Airplane

In every airplane it will be found that the center of gravity is some distance behind the wheel axle. When an airplane is landing the ground friction acting at the surface of the wheels is equal and opposite to the inertia force at the center of gravity produced by the deceleration or slowing down of the air-

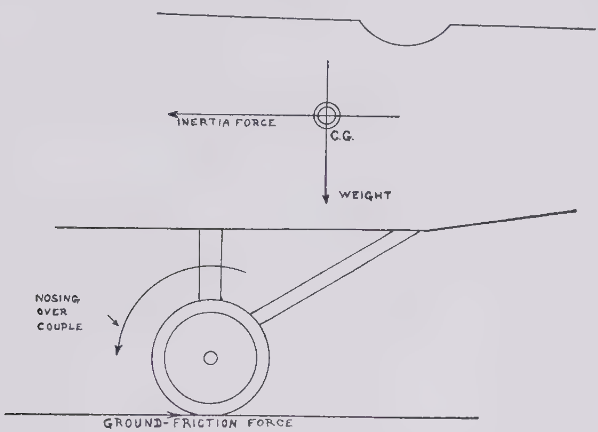


FIGURE 82

plane. These two forces produce a nosing over couple as illustrated in Figure 82. But if the center of gravity of the airplane is behind the wheel center, then an opposing couple about the wheel base is produced by gravity. For design purposes there is a very useful rule to fix the position of the wheels, with the propeller axis horizontal, between the line joining the center of gravity and the wheel axle, and the vertical through the wheel axle must not be less than 12 degrees and no bigger than 17 degrees (see Figure 83).

With unbraked wheels, the coefficient of ground friction is

rarely greater than 10 percent; (for example, if a plane weighs 2,000 pounds, the ground friction force will be 200 pounds.) With the application of brakes and wheels locked, the coefficient of ground friction may be as high as 55 percent. Therefore, the friction force, the deceleration, and also the nosing over couple are much greater with the application of brakes. When brakes are used, the wheel axle is therefore placed a good deal farther ahead, and the angle mentioned in

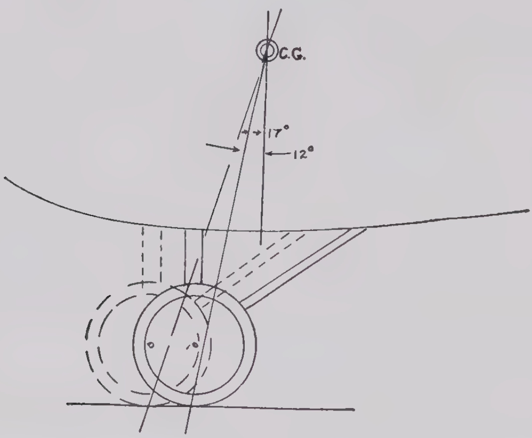


FIGURE 83

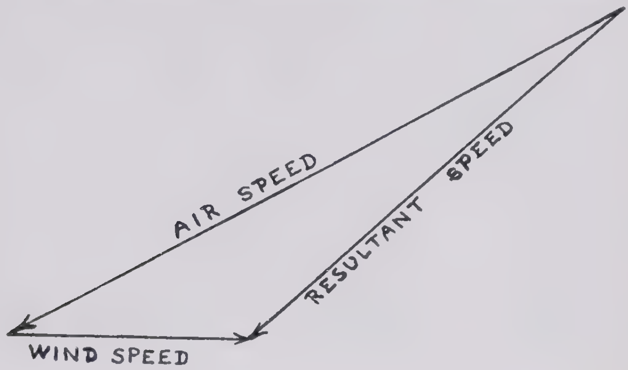
the preceding paragraph is likely to be 25 degrees rather than 12 or 17 degrees.

Unfortunately with the center of gravity farther back relatively to the wheel center, a greater proportion of the load is carried on the tail skid. This in turn means that it is somewhat harder to raise the tail at take-off. Also with a heavier tail load in taxying the surface of the airdrome is apt to suffer from the tail skid shoe. These difficulties do not seem to be insurmountable, but where front wheel brakes are employed, a tail wheel instead of the conventional tail skid seems advisable.

Effects of Wind

One of the first things a student pilot learns is always to land into the wind and to check the direction of the wind from the wind cone or "sock" when approaching a field. The reasons for this rule are obvious.

The pilot cannot tell either the direction of a steady wind without some external reference point to go by. The plane becomes part and parcel of the atmosphere. Nevertheless, the



GLIDING AGAINST THE WIND

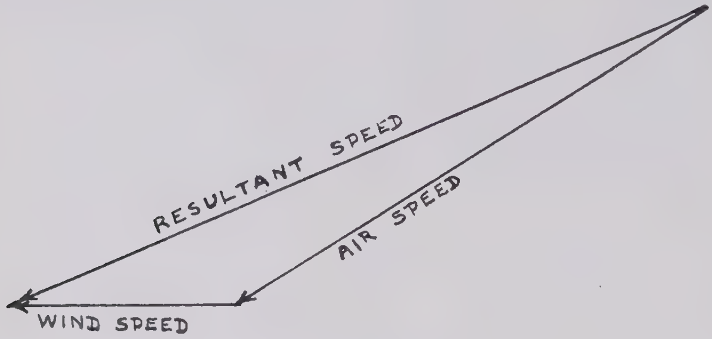
FIGURE 84

speed relative to the earth is compounded of the wind velocity and the air speed of the airplane. Gliding against the wind, the plane will, at a given angle of incidence and a given air speed, glide more steeply relative to the earth. This is illustrated by the diagram of Figure 84 where the two velocities are compounded geometrically.

When gliding with the wind, a lesser horizontal distance is covered for a given loss of altitude as illustrated by Figure 85. Therefore, it is more difficult to glide into a field flying with the wind.

Again when landing against the wind, the speed relative to

the ground is less and the danger of damage to the undercarriage is lessened.



GLIDING WITH THE WIND.

FIGURE 85

Again when landing against the wind the length of landing run is reduced. In fact, if the wind speed is exactly equal to the landing speed, the plane will come to rest where it first

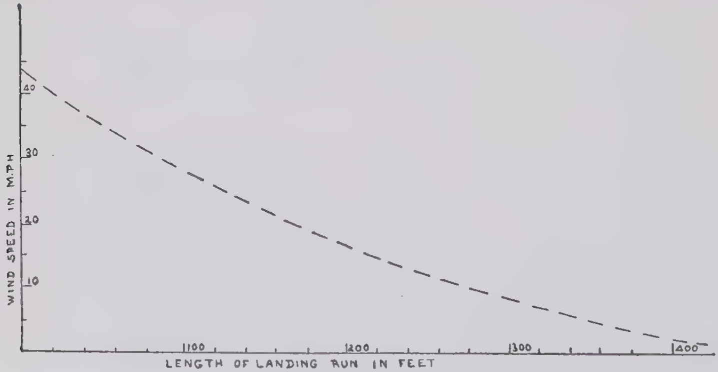


FIGURE 86

touches the ground. The way in which the landing run is reduced by a head wind depends on the design of the plane the

coefficient of ground friction, etc. Figure 86 shows a typical instance of how the landing run is reduced by head winds of various intensities.

Why a Field with Obstacles at the Boundary Has to Be Larger

The effective length of a field runway is reduced by an obstacle of some height at the boundary. If there is no obstacle, the pilot can start his landing glide well ahead of the field and land at the very boundary. When there is an obstacle of say 50 feet, and with a glide of 1 in 7, he can only land $50 \times 7 = 350$ feet from the boundary as illustrated in Figure 87. An effective decrease of runway is calculated in this fashion by the Department of Commerce in rating airports.

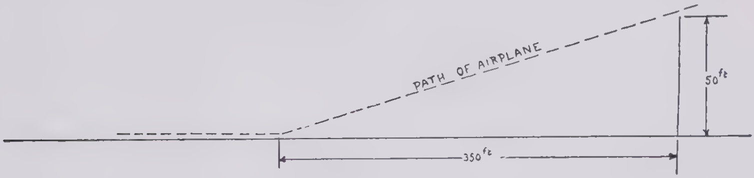


FIGURE 87

Questions

1. The hypothetical machine of Chapter 7 is gliding at an incidence of 1 degree. What is the L/D of the plane at this incidence? What is the air speed? What is the angle of the glide path with the horizontal? *Answer:* $L/D = 13.8$, $V = 78.1$, $\theta = 4° 20'$.

2. If the pilot could suddenly change the incidence to that of maximum Ky just before touching the ground, what would be the lift of the wings at this instant? *Answer:* $L = 3900$ pounds.

3. A manufacturer advertises a monoplane weighing 2,600 pounds, and having a wing area of 200 square feet as having a landing speed of 35 miles an hour. How far off is he likely to be? *Answer:* Using Ky max. as .0036, Landing Speed = 60 m.p.h.

4. A student lands a machine without flattening out from a glide of 6 degrees to the horizontal, the air speed being 80 miles an hour. What will be the vertical velocity on striking the ground? *Answer:* 12.35 feet per second.

5. A plane is gliding at 70 miles per hour, on a glide path of 1 in 7. There is a horizontal tail wind of 20 miles per hour. What will be the steepness of the glide relative to the ground? *Answer:* 6°18′.

6. A field has a row of trees at its boundary, 50 feet high. The hypothetical machine of Chapter VII is gliding over this obstacle at its best angle of glide. Its landing run is 300 feet. How far from the base of the trees will it land? *Answer:* 986 feet.

CHAPTER XI

TAKE-OFF AND CLIMB

Forces on the Take-off

During the take-off run there are the following forces acting on the airplane:

1. The thrust of the propeller pulling it forward.
2. The inertia of mass of the airplane resisting acceleration.
3. The friction of the ground.
4. The aerodynamic resistance or drag of the airplane.

It is the object of the pilot to make as quick and short a take-off run as possible, and we shall discuss the measures he can adopt to this end.

Take-off on Smooth Ground

The coefficient of ground friction on smooth ground is generally less than .05, so that the ground force is less than one-twentieth of the weight resting on it.

Since the lift over drag ratio L/D of an airplane is far less than twenty, it follows that on smooth ground there will be less total resistance (ground friction and air drag) during the take-off run, if the airplane is supported more by the ground than by the lift of the wings.

In fact, theory and experiment both show that the best way to get up speed is to place the wing in "flying position" when it has little lift but also little drag, with the tail up.

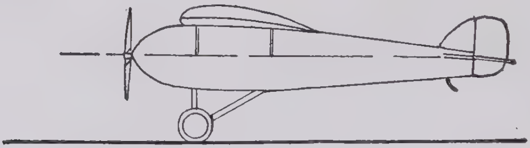
Besides where a tail skid is employed, the drag of the skid increases the resistance very much.

Therefore the pilot endeavors to raise the tail as quickly as possible, by depressing the elevators.

On a modern machine, with powerful engine, and the elevators in the slipstream of the propeller, it is possible to raise the

tail very quickly (even if the center of gravity is well back of the wheels as is the case where wheel brakes are employed).

When the airplane is once in the flying position as illustrated in Figure 88, the control stick must be eased back, and the elevator brought back into almost neutral position, otherwise turning moment of the elevator may bring the machine over into a position where the propeller strikes the ground.



TO MAKE THE QUICKEST TAKE-OFF ON SMOOTH GROUND, PUT PLANE IN "FLYING POSITION."

FIGURE 88

Take-off on Rough Ground

If the ground is rough, and the ground friction high, then it is advisable to raise the tail skid only slightly and to keep the wings at a high angle of incidence, lifting as much as possible.

Correct Take-off

If the airplane has been put into "flying position" and this position is correctly maintained the airplane will eventually lift itself off the ground without further intervention by the pilot.

The airplane should then be held level two or three feet off the ground, until an additional reserve of speed is attained. Then the nose of the plane is raised gently until the best climbing altitude is obtained.

Of course when the airplane lifts itself off, in flying position, with a small angle of incidence, the lift coefficient is less than the maximum. Therefore the speed of take-off will be higher than the stalling speed.

The pilot can leave the ground at only a little above stalling speed, by raising the nose after he has attained a fair speed.

He will then get off the ground more quickly than by the automatic, flying position method.

The question arises as to why raising the nose to leave the ground is not the better method?

The answer is that he will then take to the air at only a little above stalling speed, the excess horse-power will be small, and the climb very poor.

Also climbing near the stalling speed may readily lead to stalling itself, which as we have stated previously may lead to serious difficulties.

What Makes for Quick Take-off?

Smooth ground will naturally help take-off.

So will a "clean" airplane which has low resistance during take-off.

Low weight per horse-power will of course give a large propeller thrust for a given weight of airplane. Designers cannot always employ a low weight per horse-power because other factors such as pay load, cost of engine and fuel enter into the problem.

Low loading per square foot of wing area gives low minimum flying speed, and a low climbing speed. Therefore low wing loading will help the take-off considerably. Low loading per square foot means of course a reduced top speed and entails other disadvantages.

The variable pitch propeller, when made thoroughly practical, should be of real help on the take-off. For high speed, a high propeller pitch is necessary. To get the maximum thrust at take-off, the pitch should be as low as possible. In a fixed bladed propeller the two requirements are contradictory; the variable pitch propeller reconciles them.

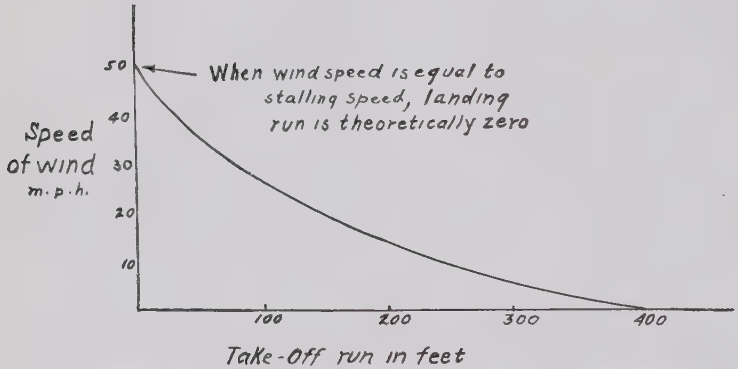
Taking-off into the Wind

Flying instructors insist quite rightly that take-off should always be made into the wind.

If an airplane which takes off at a normal air speed of 45 miles per hour, heads into a wind of 20 miles, the ground speed

at take-off will only be 25 miles an hour. Therefore heading into the wind, the acceleration needed is less, and there is less work in overcoming ground friction. A take-off into the wind is therefore both quicker and shorter than in calm air. Figure 89 illustrates the way in which the length of take-off varies with a head-on wind. It is strange to think that if the wind speed is equal to the normal take-off air speed, the airplane need not run along the ground at all before getting into the air.

Also when taking-off into the wind the relief from the lift of the wings is much greater, and bumpy ground produces less shocks.



HOW LENGTH OF TAKE-OFF VARIES WITH HEAD-ON WIND
FIGURE 89

Even if there is a head-on wind for take-off, careful pilots take all the run they can get, as a precaution against possible difficulties, and are likely to taxi to the very end of the flying field, on the leeward side. It is only in passenger hopping where flight after flight has to be made rapidly that this rule is sometimes unjustifiably broken.

Conversely, if taxying with the wind, the ground speed at take-off is higher, and the landing roll longer. Moreover no relief of the weight of the airplane is possible from the lift of the wings until a ground speed higher than the wind speed is

reached. Shocks between wheels and ground are high and unpleasant riding follows.

Best Climb

From the curves of power available and power required given in Chapter 6, it can be seen that there is one air speed at which the excess horse-power (that is the difference between power available and power required) is a maximum. The best climb occurs at this air speed. Some experimental flying is needed before the best air speed for climb can be determined. A practical rule for determining best climbing speed is:

Best climbing speed = Stalling Speed + $\frac{}{3}$ (Top Speed—Stalling Speed)

Steepest Climb

There is a distinction, which is often forgotten between best climb and steepest climb.

Best climb is the highest rate of vertical ascent. Fast climb is particularly important for military machines, because a fighting craft must be able to ascend rapidly to great heights to out-maneuver an enemy.

Steepest climb is not the most rapid climb but the climb at the greatest angle to the horizontal. For commercial airplanes, particularly when required to get out of fields surrounded by obstacles, ability to climb steeply is perhaps more important than rapidity of climb.

A fast military airplane of low loading per horse-power and high loading per square foot will climb much faster than a slower commercial machine of low wing loading, but not as steeply.

In the steepest climb an airplane is capable of, the excess horse-power and the rate of climb will both be less than at best climb, but the air speed will be less also.

Climbing With and Against the Wind

We have seen what importance the direction of the wind has in take-off. On the climb, particularly when clearing obstacles

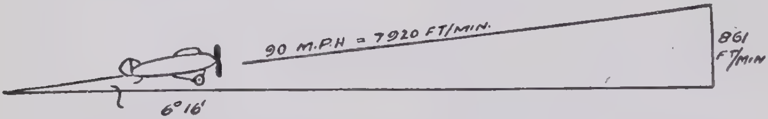
surrounding a field, it is equally important to head into the wind.

The path of an airplane in space is given by the geometrical resultant of the speed relative to the air and of the speed of the wind itself.

When climbing against a head wind the rate of vertical ascent at a given air speed is precisely the same as in calm air. But the horizontal velocity relative to the ground is decreased. Hence the path in space is steeper. Conversely when there is a following wind, the path in space is less steep.

Example

1. The hypothetical airplane of Chapter 6 has a gross weight of 1,600 pounds. At 90 miles an hour, the excess horse-power is 41.7 horse-power. What is the rate of climb? What is the angle of climb?



A PLANE HAVING AIR SPEED ON THE CLIMB OF 90 MILES PER HOUR HAS A RATE OF CLIMB OF 861 FEET PER MINUTE. THE ANGLE OF CLIMB IS 6°16"

FIGURE 90

The excess horse-power goes into work against gravity. Therefore rate of climb in feet per minute

$$= \frac{\text{excess power in foot pounds per minute}}{\text{gross weight in pounds}}$$

$$= \frac{41.7 \times 33{,}000}{1600} = 861 \text{ feet per minute}$$

The speed along the flight path in feet per minute is

$$90 \times 1.47 \times 60 = 7920 \text{ feet per minute}$$

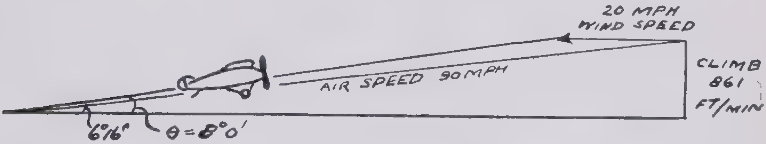
Therefore as illustrated by Figure 90,

$$\text{Sin}\theta\text{, where }\theta\text{ is the angle of climb is }\frac{861}{7920} = .109$$

and the angle of climb is approximately 6°16′ as can be ascertained from a table of natural sines in any book on Trigonometry.

2. If the airplane of the previous example is flying against a horizontal wind of 20 miles an hour, what will be the steepness of the path in space?

As illustrated by Figure 91, the rate of vertical ascent will remain unchanged.



CLIMBING AGAINST A HEAD WIND, RATE OF CLIMB IS UNCHANGED, BUT PATH IN SPACE IS STEEPER THAN IN CALM AIR.

FIGURE 91

The horizontal component of the air speed is

$7920 \times \cos\ 6°\ 16' = 7920 \times .9974 = 7900$ in feet/minute.

The wind velocity in feet per minute is

$20 \times 1.47 \times 60 = 1760$ feet.

Therefore the resultant horizontal velocity is

$7900 - 1760 = 6140$ feet per minute

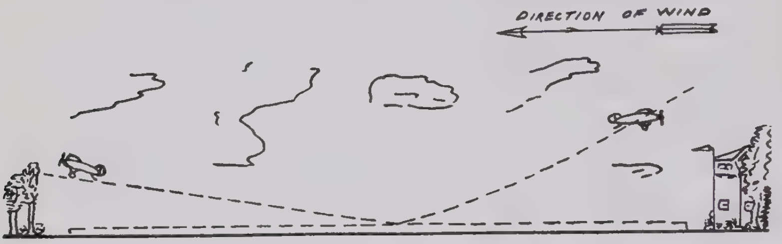
If θ is the angle of climb in space,

$$\tan\theta = \frac{\text{rate of ascent}}{\text{resultant horizontal velocity}} = \frac{861}{6140} = .141$$

and θ is now 8° 0′ which is considerably steeper than in calm air.

Figure 92 illustrates the effect of head and following wind

on the climb, and shows that climbing against the wind surrounding obstacles can be cleared much more readily.



IT IS EASIER TO CLEAR AN OBSTACLE CLIMBING AGAINST A HORIZONTAL WIND.

FIGURE 92

Stalling on the Climb

We have stated that a steeper angle of climb can be achieved by using an air speed somewhat less than that of best climb. It is not advisable, however, to climb at speeds approaching stalling speeds. The excess power then available is small, and if the angle of incidence is increased either by a movement of the control stick or by a gust of wind, a stall may follow. With the engine still functioning recovery is fairly easy.

A more dangerous case is when the engine suddenly fails on a steep climb. With the engine out of commission the natural flight path in space is downward, whereas the nose of the plane is at a large angle above the horizontal. Therefore the angle between the wing and the flight path becomes very large (as shown in Figure 93) and a violent stall may ensue. We shall consider later in more detail the phenomena involved. It is sufficient for the time being to state, that if the engine fails on the climb, the proper thing for the pilot to do, is to push forward on the stick, and try to bring the nose down, so that the wing is brought to a smaller incidence relative to the flight path, and push straight forward. There should above all no attempt be made to turn back into the airdrome, as a spinning nose dive

is then likely to occur. A great many accidents have followed incorrect action by the pilot under these circumstances.

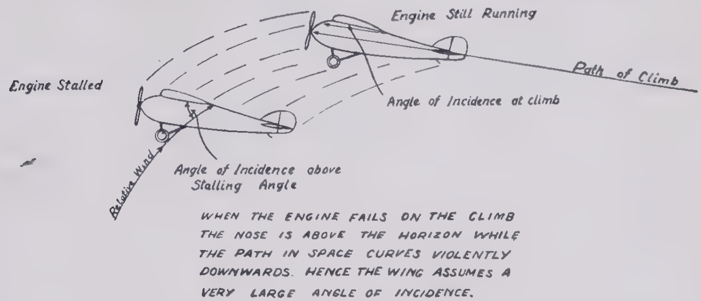


FIGURE 93

Problems

1. The plane of 1,600 pounds, wing area of 200 square feet, has a maximum lift coefficient of .00320. What is the stalling speed?

Answer: 50 miles per hour.

2. Suppose that this plane is put into flying position, with the wing at 2 degrees incidence, and a Ky of .00140. When the plane has rolled along the ground long enough to attain a speed of 30 miles per hour, what proportion of the load will be carried by the wings, and what proportion by the wheels?

Answer: 250 pounds carried by wings, 1,350 by wheels.

3. If the pilot allows the plane to lift itself automatically in flying position, how much higher will the air speed be than the stalling speed?

Answer: The air speed will be 76 miles per hour or 26 miles more than the stalling speed.

4. Would you consider the take-off of Problem 3 satisfactory? If not, how would you modify it?

5. What would you estimate to be the best climbing speed of an airplane whose stalling speed is 60 miles an hour, and maximum speed 150 miles?

Answer: 90 miles an hour.

6. In the examples of this Chapter, the plane is climbing at 90 miles per hour air speed in calm air, and the rate of climb is 861 feet per minute. What is the horizontal velocity relative to the ground?

Answer: 7,840 feet per minute.

7. If in the preceding problem, the plane takes off at the center of a field which is 1,500 feet from the edge of the field, what height of obstacle can the pilot clear?

Answer: 163.5 feet.

8. If in the climb of the preceding problem, there is a horizontal head wind of 20 miles per hour, what height of obstacle will the pilot now be able to clear?

Answer: 212.3 feet.

9. If in the climb of Problem 7 there is a tail wind of 20 miles per hour, what height of obstacle will the pilot clear?

Answer: 134.3 feet.

CHAPTER XII

LONGITUDINAL STABILITY

Mechanical Analogies for Stability

The static stability of a body is its ability to return unaided to the original position from which it has been displaced.

When a cone is placed on its base, as in Figure 94, the cone is stable. Tilted slightly to one side, it will return to its

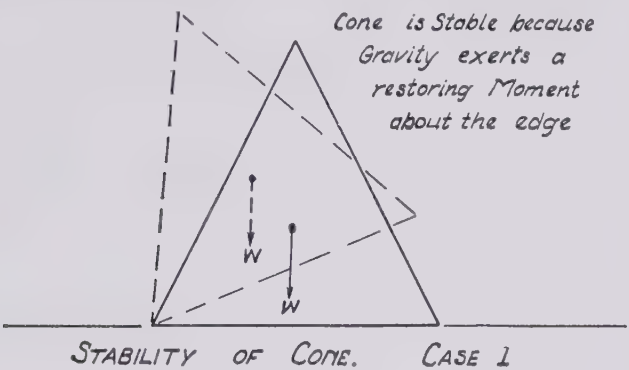


FIGURE 94

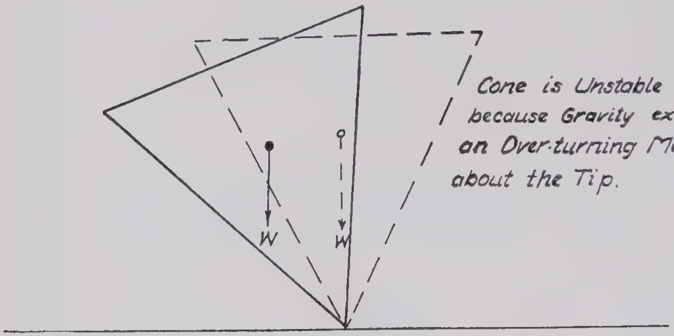
original position, because the force of gravity acting through the center of gravity has a restoring moment about the edge in contact with the ground.

If the cone, by skilful handling is balanced for an instant on its apex, as in Figure 95, the slightest displacement will cause it to topple over sidewise. The cone in this position is said to be unstable.

Now if the cone is placed on its side, as in Figure 96, and is slightly displaced, it will neither return to its original position

nor topple. It is neither stable nor unstable, but in neutral equilibrium.

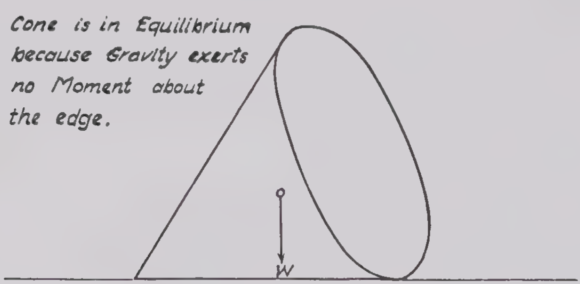
So much for static stability.



STABILITY OF CONE CASE 2.

FIGURE 95

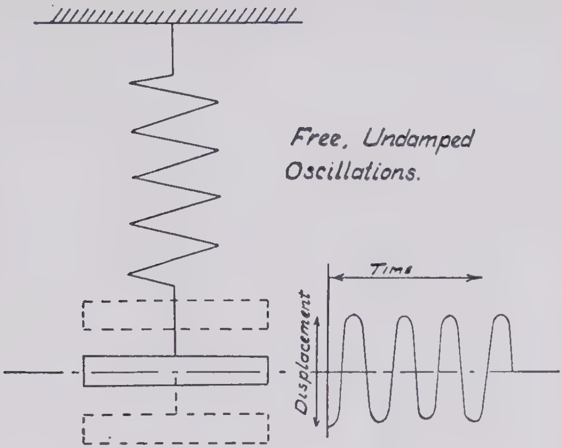
If a spring is pushed down by a man's hand, as shown in Figure 97, and is then released, it will oscillate up and down, and only come to rest in its original position after a number of



STABILITY OF A CONE

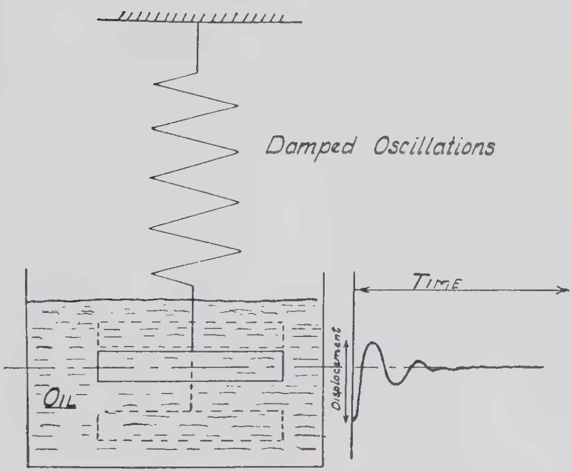
FIGURE 96

oscillations. The spring is statically stable, but its oscillations are undamped. If the same spring is placed in a heavy viscous oil, Figure 98, the oscillations before coming to rest will be



SPRING - STATICALLY STABLE

FIGURE 97



SPRING - STATICALLY AND DYNAMICALLY STABLE.

FIGURE 98

much fewer in number. The spring is damped, and has not only static, but dynamic stability as well.

An Ordinary Wing Alone Would Give an Unstable Airplane

In Chapter 5 of this book we discussed the properties of the Clark Y airfoil, and in Figure 99, the characteristics are replotted for reference.

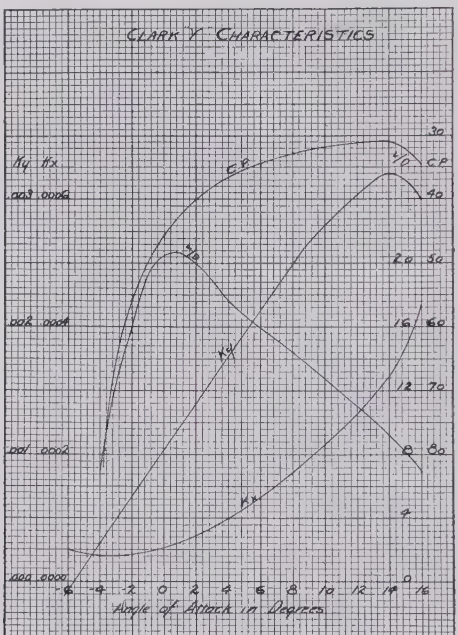
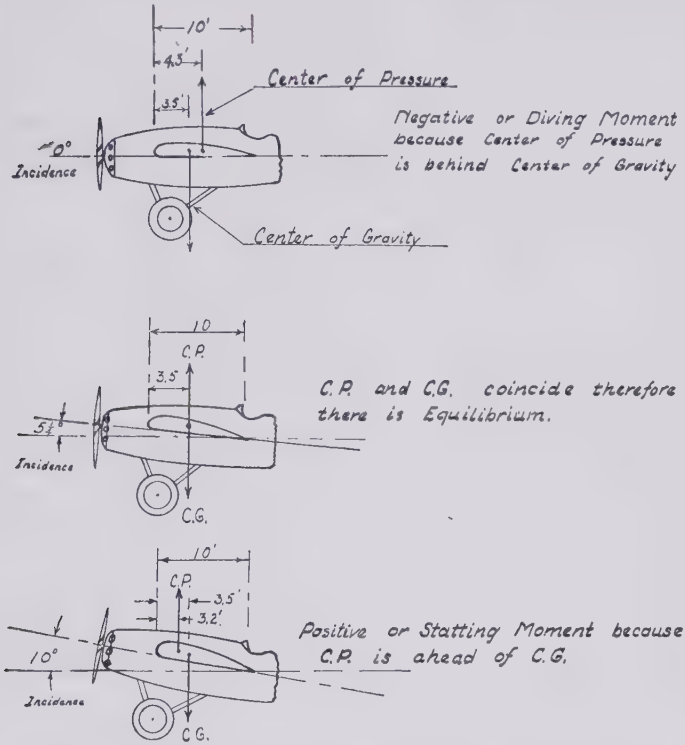


FIGURE 99

Suppose we had a rudimentary airplane, supported by a wing of 10 foot chord, having no tail surfaces (as shown in Figure 100) and a center of gravity situated on the wing chord, at 35 percent of the chord, or $3\frac{1}{2}$ feet from the leading edge. From the chart of Figure 99, the center of pressure

of the wing will pass through the center of gravity when the angle of incidence is about 5¼ degrees. Disregarding the effects of drag and propeller thrust for the time being, the air-



RUDIMENTARY PLANE WITHOUT TAIL SURFACES.
FIGURE 100

plane will be in equilibrium at this particular angle of incidence.

Now imagine that either a movement of the control stick or a sudden gust raises the nose of the airplane, until the angle of incidence is 10 degrees. From the chart we see that the center

of pressure is now at 32% of the chord, and therefore the lift is .3 feet ahead of the center of gravity. Evidently the rudimentary airplane tends to nose up even more.

If on the other hand, the airplane should for some reason go down by the nose till the incidence is 0 degrees, the center of pressure will move back to 45% of the wing chord, and the lift will be back 1 foot of the center of gravity, therefore there will be a tendency to push the nose down still further.

Evidently an airplane with wing alone will be unstable.

How the Horizontal Tail Surfaces Produce Stability

In figure 101 this rudimentary airplane is equipped with a horizontal tail surface, disposed at a negative angle to the wing chord. If the tail surface is symmetrically double cambered, and if downwash effects of the wing are neglected, then there will still be equilibrium of the airplane at 5¼ degrees incidence, provided the tail surface is then at zero degrees.

Now imagine the wing again raised to 10 degrees incidence. The tail surfaces are now at $(10 - 5\frac{1}{4}) = 4\frac{3}{4}$ degrees incidence, and therefore exercise an upward lift, and the moment of the tail surfaces counteracts the moment of the wing, and if the tail surfaces are large enough the plane will swing back to its original position.

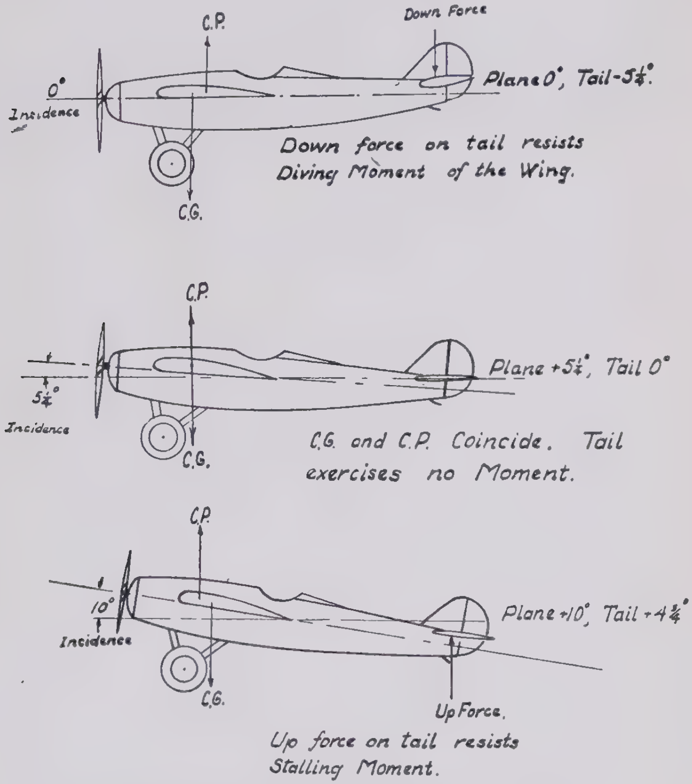
If the plane should nose down till the incidence of the main wing is zero; the tail surface will now be at a negative incidence of —5¼ degrees and the tail lift force will act downwards, thus again restoring equilibrium.

Definition of Pitching Moment

The longitudinal moment about the center of gravity produced by the air forces on the wing, tail surfaces, etc., is termed the pitching moment.

If the pitching moment is such as to raise the nose of the plane it is said to be a positive or stalling moment. If the pitching moment tends to lower the nose, it is said to be a negative or diving moment (see Figure 102).

If a plane is trimmed (that is in equilibrium at a certain angle of incidence and flying speed) then the pitching moment at any angle should always bring the plane back to its original



RUDIMENTARY PLANE WITH TAIL SURFACES

FIGURE 101

incidence. This is illustrated in Figure 103. At 5¼ degrees incidence, the pitching moment is zero, and the plane is in equilibrium. If the incidence is diminished below 5¼ degrees

the pitching moment should become positive, and nose the plane back to the 5¼ degrees incidence. If the incidence is increased above 5¼ the pitching moment should become negative, so as

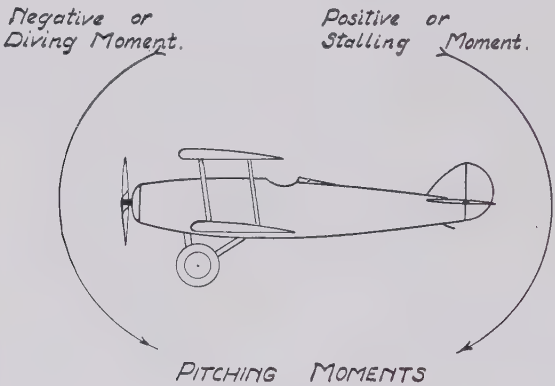


FIGURE 102

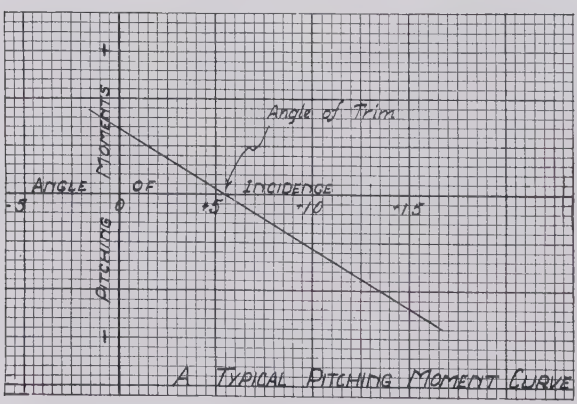


FIGURE 103

to nose the plane down. The pitching moment curve should have therefore a negative slope, or slope downwards from left to right to give stability.

Will a Given Airplane Be Stable?

Suppose our monoplane of 10 foot chord, center of gravity at 35% of the chord, span of 60 feet, wing area of 600 square feet with a loading per square foot of 10 pounds be longitudinally stable, if the horizontal tail surface has an area of 15% of the wing area, that is 90 square feet, and if the arm of the tail surfaces (that is the distance from the rudder post to the center of gravity) is three times the chord, that is 30 feet (see Figure 104).

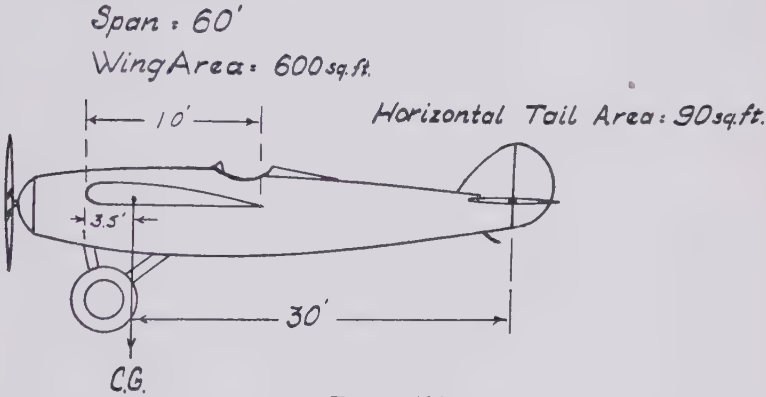


FIGURE 104

So many factors are involved in longitudinal stability, characteristics of the main wing, downwash, shape of the fuselage, characteristics of the tail surfaces, etc., that the calculation of longitudinal stability is extremely uncertain, and a wind tunnel test or a test in full flight is the only criterion. The following calculation is only approximately correct, but illustrates the ideas involved:

Trim at a Given Angle of Incidence

Suppose that we want the plane to trim at 1 degree angle of incidence for the main wing (which should be about right for cruising). At what angle should the stabilizer be set?

At 1 degree incidence Ky = .00125. Since area is 600 square feet, and loading is ten pounds per square foot

$$V = \sqrt{\frac{W}{KyA}} = \sqrt{\frac{6000}{.00125 \times 600}} = 89 \text{ miles per hour.}$$

At 1 degree incidence the center of pressure is at 42.5% of the chord. The moment of the lift about the center of gravity is a negative or diving one, and is equal to 6,000 × [4.25 — 3.50] = 4,500 foot pounds.

The horizontal tail surface has an arm of 30 feet, therefore the downward force on it must be $\frac{4500}{30}$ = 150 pounds.

What Ky should the tail surfaces be working to give 150 pounds lift?

$$150 = Ky\ (\text{area of tail surfaces})\ .V^2$$
$$= Ky\ (90) \times 89^2$$

Therefore the required Ky = .00021

Because of certain vortices at the tip of the main wing, the air is deflected downwards and has an angle of downwash. (We shall go fully into this in a later chapter.)

Lieutenant Charles N. Monteith in his excellent book on Aero-dynamics, estimates that

the angle of downwash in deg. = 1980 Ky of main wing + 0.25
= 1980 × .00125 + 0.25
= 2.62 degrees

The air strikes the tail surfaces at 2.62 degrees above the horizontal, therefore, as shown in Figure 105.

The characteristics of a typical tail surface are shown in Figure 106. To have the required Ky of .00021 the tail surfaces must be set at 1 degree to the effective wind, or at (2.62 — 1) = 1.62 degrees to the horizontal. The main wing is at 1 degree to the horizontal. Therefore, the tail surface should be at .62 degrees to the wing.

This apparently contradicts our previous statement that for stability at low angles of incidence, the stabilizer should be at

a negative angle to the wing chord. It is aerodynamically at a negative angle, however, since the "downwash" changes the aerodynamic conditions.

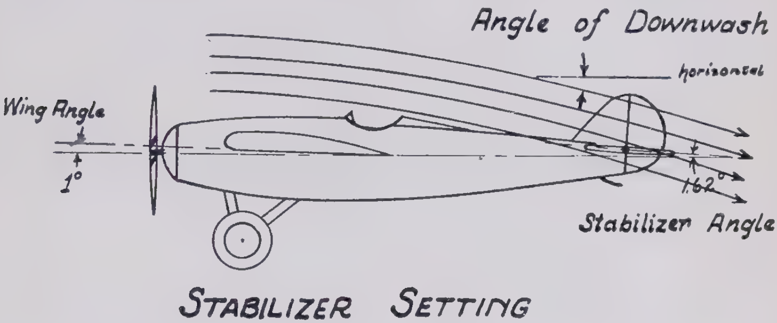


FIGURE 105

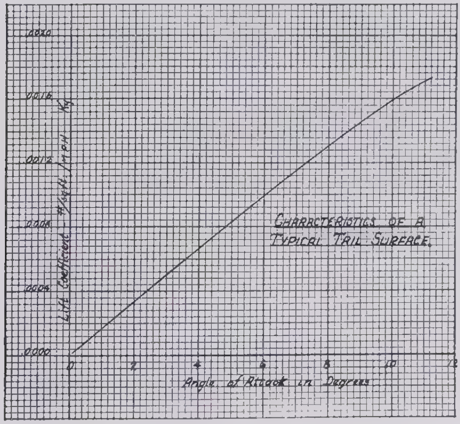


FIGURE 106

Problem

1. Given a monoplane with a Clark "Y" wing 40 feet in span and 5 feet in chord. The center of gravity is on the chord at 30% of the chord from the leading edge of the wing. The tail

area is 30 square feet, and the distance from the center of gravity to the tail post is 15 feet. If the stabilizer and elevator are set at 2° to the wing chord, draw a curve of pitching moments against angle of attack. Consider the velocity constant at 100 miles per hour so that the curve obtained will be similar to that resulting from a wind tunnel test.

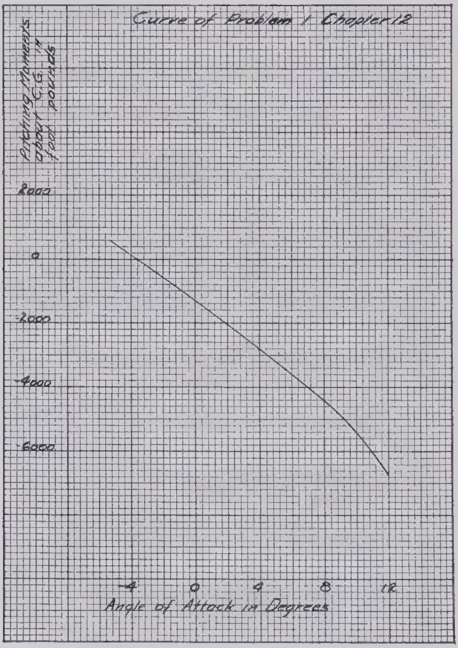


FIGURE 106A

2. Considering the ship of problem (1) to trim at 1° angle of attack to the main wing, what is this trimming velocity, and what stabilizer setting will be necessary if the ship weighs 2,000 lbs.?

Problem (1)

Solution

$$\text{Moment of Wings} = -\,Ky\ AV^2\ (C.P.-30)S$$
$$= -\,Ky\ (200)\ (100)^2\ (C.P.-30)S$$
$$= -\,10{,}000{,}000\ Ky\ (C.P.-30)$$
$$\text{Moment of Tail} = +\,Ky_{(tail)}\ A_{tail}\ V^2\ (15)$$
$$= +\,Ky_{(tail)}\ (30)\ (100^2)\ (15)$$
$$= +\,450{,}000\ Ky_{tail}$$

d = angle of downwash $= 1{,}980\ Ky + .25$

Tail angle $= (2^\circ + d)$

Ky_{tail} from lift curve Tail (fig. 106)

1	2 Ky	3 C.P.—30	4 Ky(CP—30)	5 $M_w=(4)$ $\times SAV^2$	6		7	8 Mcg
—4	.00030	.64	.000192	—1920	.84	2.84	2046	126
0	.00100	.155	.000155	—1550	2.23	—.23	1660	—1384
4	.00180	.068	.000122	—1220	3.81	2.19	—1580	—2800
8	.00250	.028	.000070	—700	5.15	4.85	—3500	—4200
12	.00300	.015	.000045	—450	6.20	7.80	—5620	—6070

Problem (2)

$$V = \frac{W}{KyA} = \frac{2000}{.00122 \times 200} = 90.6 \text{ m.p.h.}$$

At 1° C.P. = 42.5% chord

The moment about c.g. $= 2000\ (42.5 - 30)\ S = -\,1250$

$$\text{Horizontal tail surface downward force} = \frac{1250}{15} = 83.4 \text{ pounds.}$$

$83.4 = Ky \times 30 \times 90.6^2$

$Ky = .00034$

$$\text{Angle of downwash} = 1980\ Ky + 0.25$$
$$= 1980 \times .00122 + 0.25$$
$$= 2.69^\circ$$

To have a $Ky = .00034$ the tail surfaces must be set at 2° to resultant wind (2.69 —2.0) = .69° to horizontal, and as the main wing is at 1° to the horizontal, the stabilizer must set —.31° to the wing.

CHAPTER XIII

LONGITUDINAL STABILITY (Continued)

Use of the Wind Tunnel in Studying Longitudinal Stability

It is difficult to obtain absolutely accurate results regarding efficiency in the wind tunnel. The wind tunnel is useful, how-

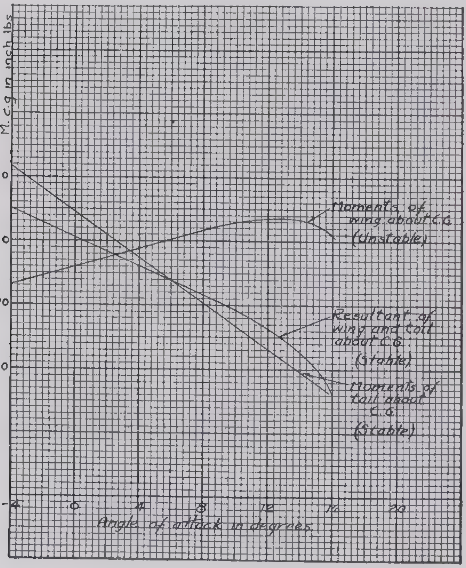


FIGURE 107

ever, in giving comparative values of efficiency, and is very reliable as regards longitudinal stability. So that our readers may be able to interpret wind tunnel test reports, we shall

continue the study of the stability of our airplane on a wind tunnel scale.

The monoplane described in the previous article had 10 foot chord, and 60 foot span. A wind tunnel model of 1/20th scale with chord of 6 inches and span of 36 inches would be quite convenient. A wind tunnel speed of 60 miles per hour will be assumed in our calculations.

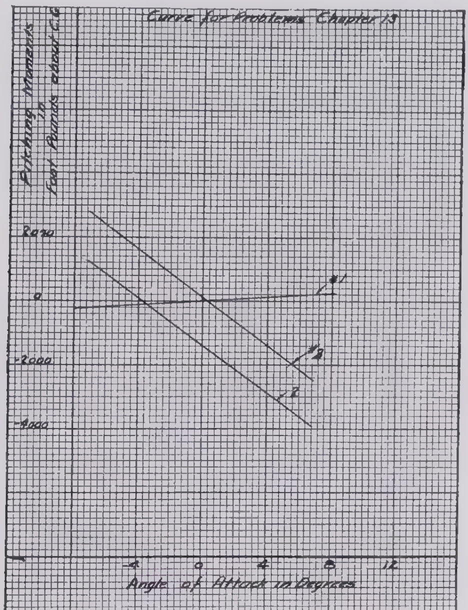


FIGURE 107A

As stated in the previous chapter, the center of gravity is taken at 35 per cent of the chord or 2.1 inches from the leading edge. The arm of the tail surfaces is 18 inches on the model, and their area is 32.4 square inches.

With these assumptions, calculations as in Example 1, can be made for the moments about the center of gravity of the

wing alone. Plotted in Figure 107, the curve of the wing moments is seen to be unstable; at large angles of incidence there is a stalling moment, and at small angles of incidence a diving moment.

In Example 2 the tail moments are calculated and also plotted in Figure 107. The tail moments tend to give stability, since they are diving moments at high angles of incidence and stalling moments at low angles of incidence.

When the moments due to the wing and those due to the tail surfaces are added together, the resultant curve, as shown in Figure 107, is stable.

We come to this conclusion that for the ordinary type of wing such as the Clark Y, the wing gives an unstable moment curve, which can be overcome by the stabilizing effect of the tail surfaces.

Example 1—Method of Calculating Wing Moments

If the Clark Y wing is at 4° incidence the center of pressure is at 36.5% of the chord. Therefore the distance between c. p. and c. g. is 1.5% of the chord or .09 inches. Neglecting effect of drag on moments and taking lift only into account:

$$\text{Lift} = \text{Ky } AV^2 = .00179 \times 1.5 \times 3600^2 = 9.65 \text{ lbs.}$$
$$\text{Arm of lift} = -.09 \times \cos 4° = -.0895 \text{ inches}$$
$$\text{Moment} = .0895 \times 9.65 = -.865 \text{ inch. lbs.}$$

Moment is negative since c. p. is in back of c. g.

Example 2—Method of Calculating Tail Moments

$$\text{Angle of downwash} = 1980 \text{ Ky} + 0.25$$
$$= 1980 \times .00179 + 0.25$$
$$= 3.80°$$

Angle of attack of the tail = angle of attack of wing + .62 (original setting of tail to wing) —3.80 = 4.62 —3.80 = .82°

Ky of tail at .82 degrees = .00017

Lift on tail = .00017 × .225 × 3600 = .138163

Arm of tail = 18″

Moment due to tail = 18 × .138 cos A° = 2.45 in. lbs.

Effect of Center of Gravity Position

In Figure 108, the wing moments are shown recalculated for two other positions of the center of gravity, namely, 28 and 50 per cent of the wing chord.

When the center of gravity is far forward, there is nose heaviness, but no instability for the wing alone, since the moment curve slopes down from left to right.

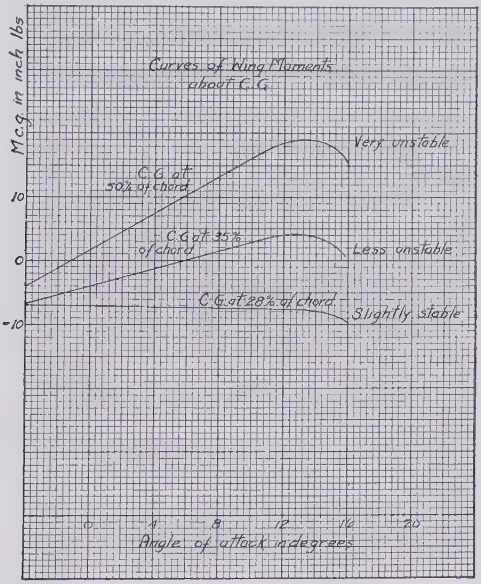


FIGURE 108

When the center of gravity is far back, the instability of the wing moment is very large, since the curve slopes markedly upwards from left to right.

It follows that it is very much harder to make an airplane stable, when the center of gravity is far back.

An airplane in which the passenger load, or mail or freight is not disposed at the center of gravity may therefore be quite

stable when fully loaded, and instable when lightly loaded or vice-versa.

Practical operators should therefore pay considerable attention to the balance of the plane. At the Croydon Aerodrome in London, all passenger machines are carefully weighed for c. g. position before they are allowed to leave the field.

A rough practical rule, frequently used in design is that the center of gravity should be at 30 per cent of the wing chord.

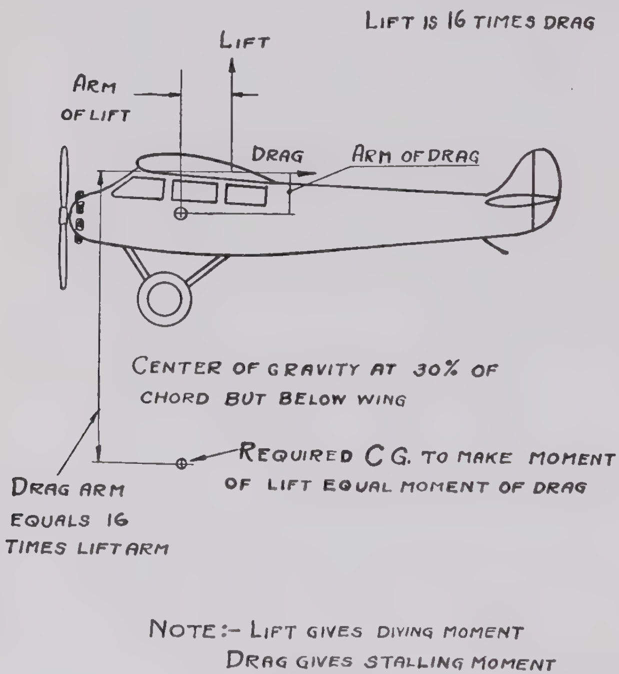


FIGURE 109

Effect of Vertical Position of Center of Gravity

The effect of the vertical position of the center of gravity on the longitudinal stability is comparatively slight.

Suppose the center of gravity is at 30 per cent from the lead-

ing edge, but far below the chord as shown in Figure 109. At 1 degree incidence the center of pressure is at 42.5 per cent of the chord. The lift under these conditions is exercising an unstable diving moment, the drag a stabilizing, stalling moment. But since the drag is much smaller than the lift, the center of gravity would have to be placed so far below the wing to secure stability as to give a totally impractical airplane.

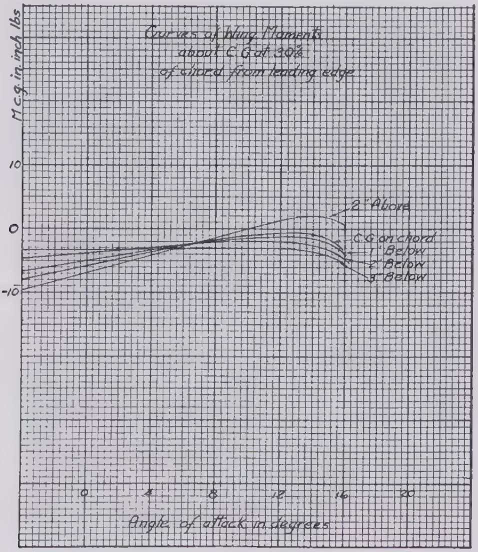


FIGURE 110

Nevertheless placing the center of gravity low down, does improve the stability somewhat as shown by the curves of Figure 110, where moments for wing alone are calculated for a fixed position along the chord. As the distance below the chord increases, so the unstable slope of the wing moment diminishes.

Conversely if the center of gravity is placed above the wing, the instability of the wing moment will increase.

It follows from this that a low wing monoplane of design otherwise similar to that of a high wing monoplane will require a larger area of tail surfaces.

Changing Trim by Changing Stabilizer Setting

Changing the stabilizer setting does not change the properties of the tail surfaces, but merely shifts the curve with relation to the angle of incidence.

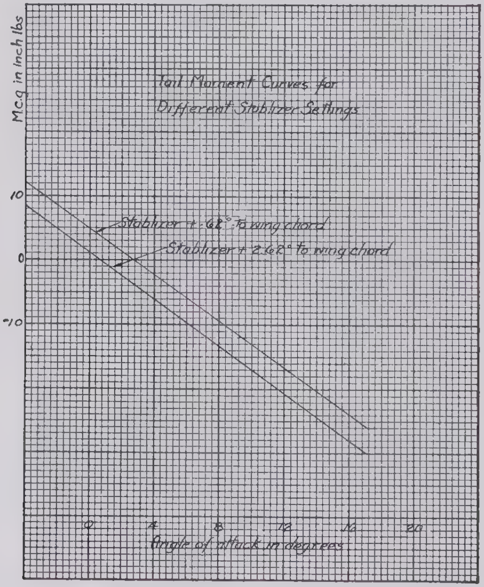


FIGURE 111

For example, if for the case illustrated by Figure 107 the stabilizer leading edge is raised so as to give the stabilizer 2 degrees more incidence, then the tail moment curve is simply shifted 2 degrees to the left, but remains parallel to itself (see Figure 111).

The resultant moment curve now passes through the zero point at a smaller angle of incidence, but its slope remains unchanged (see Figure 112).

Therefore changing the stabilizer setting only affects the trim, but not the stability.

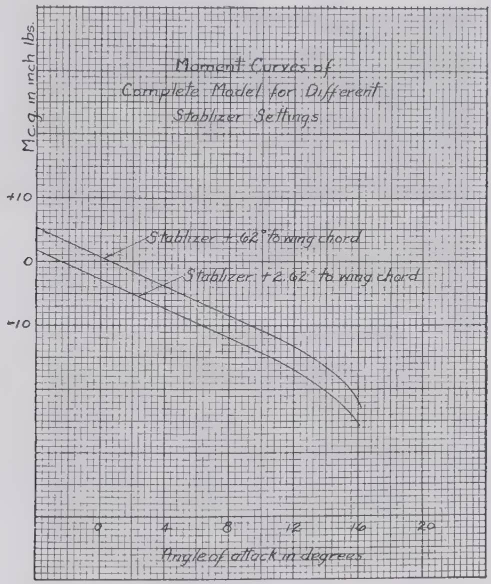


FIGURE 112

A Defect in Stability Cannot Be Removed by Changing Stabilizer Setting

If the stabilizer leading edge is raised, it will carry a lesser down load, and that is why the plane trims at a lesser angle of incidence. In other words raising the leading edge of the stabilizer will remove tail heaviness.

Conversely lowering the leading edge of the stabilizer will increase the down load on the stabilizer, and trim the plane at

a higher angle of incidence. In other words lowering the leading edge of the stabilizer will remove nose heaviness.

The adjustable stabilizer is very convenient where flights are to be made with various positions of the load, or at various altitudes but if the center of gravity is so far back that a plane approaches instability, then the instability will remain no matter what the setting of the stabilizer may be.

Slip Stream Effects and Line of Thrust Position

If, as in most modern airplanes, the center of gravity is placed well forward, say at 30 per cent of the wing chord, the center of pressure is behind the center of gravity almost through the entire flight range, and the tail surfaces are carrying a downward load accordingly.

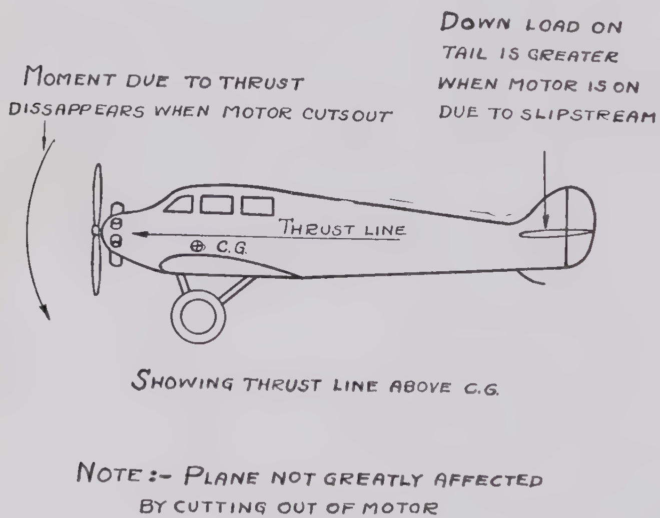


FIGURE 113

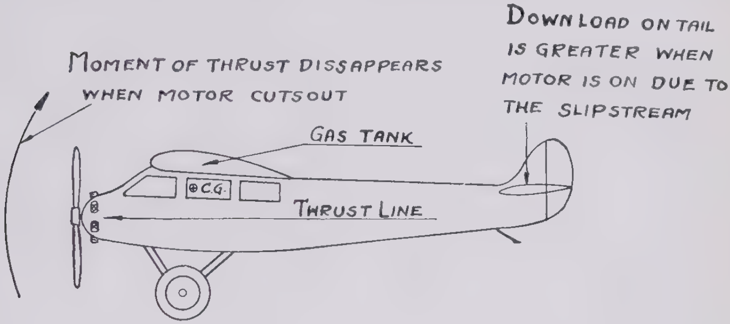
An airplane propeller develops its thrust by "pushing" on the air and accelerating it as it passes through the propeller disk. Therefore the velocity of the air in the slipstream of the

propeller is greater than the speed of the airplane as a whole.

Where the tail surfaces are in the slipstream, they will for the same flight speed be in an airstream of greater velocity with "power on" than with "power off," and will experience a greater downward force with power on than with power off.

Accordingly, if a plane is trimmed, power off, for a certain flight speed, it is likely to be tail heavy at the same speed with power on.

Conversely, if a plane is trimmed for power on at a certain



SHOWING C.G. ABOVE THRUST LINE

NOTE:-WHEN MOTOR CUTS OUT PLANE TENDS TO NOSE DOWN

FIGURE 114

flight speed, it is likely to be nose heavy at the same speed with power off.

The above remarks are almost certain to be true when the line of thrust passes through the center of gravity of the airplane.

When the line of thrust does not pass through the center of gravity the problem becomes a little more complicated.

Let us take the case of a high wing monoplane, with gasoline tank in the wing, a high position of the center of gravity and

from considerations of the pilot's vision a comparatively low thrust line, as illustrated in Figure 113.

Suppose that by stabilizer adjustment the plane is in balance with power on, and the engine is suddenly shut off or fails.

The slipstream disappears and the downward force on the tail surfaces diminishes. There is therefore a tendency for the plane to nose down. Simultaneously the moment of the thrust, which evidently exercised a stalling moment about the center of gravity, disappears. This is another reason for the plane to nose down.

In this case the balance "power off" and "power on" is quite different, and pilots will complain rightly that the ship tends to go into too steep a dive when the power is shut off.

Now let us take the case of a low wing monoplane as in Figure 114 where the thrust line is above the center of gravity. In this case when the engine is suddenly switched off, there is as before a lesser down load on the tail surfaces, but at the same time the diving moment of the propeller thrust about the center of gravity disappears, and the machine is not likely to dive steeply.

Flying boats are apt to have a very high thrust line, because designers like to keep the propeller clear off the water, and because with a pusher propeller the engine has to be put above a monoplane wing. A typical case of high propeller thrust is illustrated in Figure 115. In such a case the down load on the tail surfaces has to be very high to counteract the large nosing over couple of the propeller, and when the engine fails, the flying boat is apt to stall. Stalling when the engine fails is a worse condition than going into a sharp dive.

It is very difficult to avoid a difference in balance conditions with change from "power on" to "power off" because there are so many different factors to compromise.

A rough rule is that the thrust line should either pass through the center of gravity or that the thrust line should be a few inches above the center of gravity, so that the disappearance of the propeller thrust couple more or less balances the decrease

in the stalling moment, of the tail surfaces, when the slipstream disappears.

Position of the thrust line far above the c. g. or far below the c. g. should be avoided.

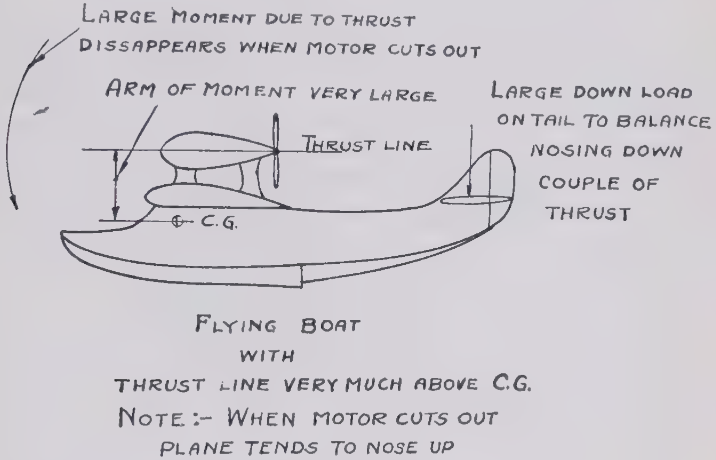


FIGURE 115

Effect of Parasite Resistance on Balance

In considering longitudinal balance and stability we have apparently neglected all other aerodynamic forces than those acting on the wing and tail surfaces. This is because parasite resistance (drag of fuselage, struts, landing gear, etc.) is apt to act fairly close to the center of gravity, and also has far less magnitude than the lift forces on the wing.

It is only in extreme cases that the resistance of certain parts has much effect on the balance. For example if two large pontoons are placed well below the center of gravity, their aerodynamic drag will then change trim because their drag will evidently introduce a nosing over couple.

The writer has been frequently asked whether the retraction of the chassis in a land plane will affect the balance very much. Simple calculation shows that it will not. A very slight down

motion of the leading edge of the stabilizer will be sufficient to give precisely the same trim with chassis withdrawn as with chassis down.

Full Flight Test of Stability

It is very easy to determine in full flight whether an airplane is stable or not.

Suppose that by the use of the adjustable stabilizer, the plane is perfectly trimmed for cruising, so that it can be flown hands off.

Push the stick forward, then release. The plane should nose down at first, oscillate once or twice and then return to its original position.

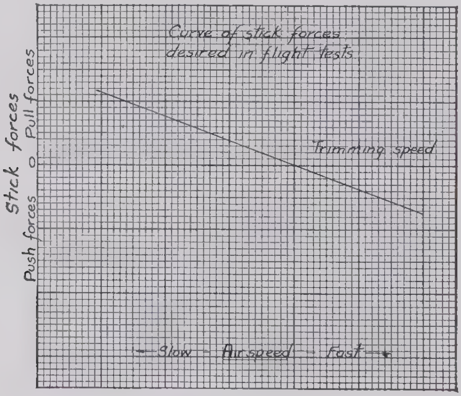


FIGURE 116

If the stick is pulled back, then released, the plane should nose up, oscillate once or twice, and then return to its original position.

Another test for stability of a more quantitative character is to use a simple spring stick force recorder.

With the ship trimmed for a certain speed, the recorder should show "push" forces on the stick for higher speeds "pull" forces on the stick for lower speeds.

The character of the "push" and "pull" forces it is desirable to have is shown in Figure 116.

Dynamic Stability

In the previous chapter we explained the distinction between static and dynamic stability, with analogy of an oil damped spring.

Static stability for the airplane can be achieved by providing a sufficient tail moment arm, either by small surfaces placed at the end of a very long fuselage, or by large surfaces placed at the end of a short fuselage.

If a machine is short coupled, however, and provided with large tail surfaces it may be statically stable but not dynamically stable. When displaced from its position of equilibrium, it will oscillate rapidly and perhaps violently about the position of equilibrium, and will take a comparatively long time to settle down.

If on the other hand a plane is equipped with a long fuselage and somewhat smaller tail surfaces, it will be not only statically stable, but also dynamically stable. The tail surfaces will act as a species of "feathering" mechanism, damp out the oscillations quickly and give an easy riding machine.

Practical Methods of Correcting for Longitudinal Instability

With the technical knowledge now available and with such apparatus as the wind tunnel at our disposal, there is no excuse for designing a machine of longitudinal instability. However, if a pilot does find longitudinal instability present, the corrective measures are fairly clear.

The most powerful corrective measure is to move the center of gravity forward. We have seen what an enormous influence the position of the center of gravity has, and if the center of gravity can be pushed forward till it is about at 30 per cent of the chord, remarkable improvement will appear in an instable machine.

It is of course easier to enunciate this rule on paper than to

put it into practice. Changing the position of the center of gravity may mean redesigning the whole machine.

Therefore the designer may resort to increasing the tail surface moment, which depends on the product of the tail arm by the tail surface area. To increase this product, the designer may (1) increase the length of the fuselage or (2) increase the area of the tail surfaces or (3) compromise and increase both the length of the fuselage and the tail surface area; which is the correct procedure depends on a great many factors, and the problem is somewhat too advanced for full consideration here.

Another possibility is to keep the same moment arm and tail surface area, but to increase the aspect ratio of the tail surfaces by lengthening their span and narrowing the chord (this of course may introduce structural difficulties). As will be shown in a later chapter the lift of an airfoil increases more rapidly with increase of angle of incidence when the aspect ratio of the airfoil is greater. The machine departs from the equilibrium position, the pitching motion evidently changes the angle of incidence of the tail surfaces. With high aspect ratio there will be a more rapid change in the lifting properties in the high aspect ratio tail surfaces, and they will provide a more powerful restoring moment.

At the same time tail surfaces of high aspect ratio will have less of their length in the slipstream, and therefore be less influenced by the power off and the power on variation.

The usual tail surfaces have an aspect ratio of 3. Unduly high aspect ratio introduces structural difficulties, and also makes the tail surfaces stall earlier, and therefore less effective at the stall condition of the main airfoil.

Ample Control as Well as Longitudinal Stability Required

There is one important point in design which is often forgotten: there should be ample longitudinal stability, but there should be also ample longitudinal control.

No matter how stable the airplane is, the elevators should be able to overcome the natural stability of the airplane. If the

elevators are not powerful enough, it may be impossible to overcome the stability at high angles of attack and therefore impossible to set the machine down at the proper landing altitude.

When the area of the tail surfaces increased therefore it may be well to increase the area of the elevators as a proportion of the total tail area.

Problems

(1) An airplane of 40 feet span, 5 foot chord, using a Clark "Y" wing, has a tail surface area of 30 square feet. The distance from the tail post to the leading edge of the main wing is 16.5 feet. The pitching moment curve of this ship is given in figure 107-A Curve No. 1. If these moments were calculated for a speed of 100 miles per hour, a stabilizer setting of 2°, and a c.g. on the chord of the main wing, what is the c.g. position used?

(2) What c.g. location for the ship in problem 1 would be needed to give curve No. 2 figure 107-A?

(3) Draw a curve of problem (2) with stabilizer set at 0° to the wing chord.

Problems

Solutions and Answers

No. 1.

$$M_w = -Ky\,AV^2\,(CP - X)5$$

$$M = -Ky\,AV^2\,(16.5 - 5x)$$

$$Mcg = -Ky\,AV^2\,(CP - x)5 - Ky\,AV^2\,(16.5 - 5x)$$

at 0° Downwash $= 1980\ Ky + .25 = 2.29°$

$A_t = 2 - 2.292° = -.29$

$$O = -.00103\ (200)\ 100^2\ (.455 - x)\ 5 - .0004 \times 30 \times 100^2\ (16.5 - 5x).$$

$$10300\ (.455 - x) = 12\ (16.5 - 5x)$$

$$x = 43.8\%$$

c.g. is at 43.8% of the chord

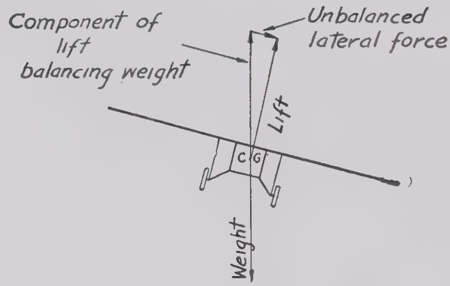
No. 2. Answer: 30%.

No. 3. Answer: See Fig. 107-A.

CHAPTER XIV

LATERAL STABILITY

The lateral motion of an airplane is far harder to understand than its longitudinal motion, because rolling and turning are so closely inter-connected, and the following simplified treatment is only approximately correct. Nevertheless it should give the student a basis on which to build his knowledge of the subject.



An airplane rolled, but flying in the same straight line as before. The roll will not tend to right the plane because the lift force passes through the center of gravity.

FIGURE 117

There Is Actually No Stability in Pure Roll

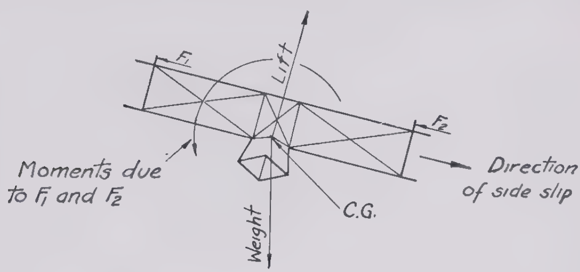
There is actually no stability in pure roll for an airplane.

Imagine an airplane which is flying horizontally, suddenly banked without any change in the horizontal motion as shown

in Figure 117, where the motion is supposed to be into the plane of the paper. The lift force will still be at right angles to the motion and will still pass through the plane of symmetry and the center of gravity of the airplane. Therefore it exercises no restoring moment about the center of gravity of the airplane. Nor does it make any difference whether the center of pressure is above or below the center of gravity.

A Roll Always Produces Side Slip

Let us study the diagram of Figure 117 again. Since the lift force passes through the center of gravity there is no



F_1 and F_2 are lateral forces on fins giving righting moments in side slip

FIGURE 118

restoring moment, but there is also no equilibrium of forces. There is an unbalanced lateral component of the lift, which must produce side slip to the right.

Fins Above the Wing, Dihedral and Sweepback

It is when the side slip occurs that a righting moment will be brought into the play, by one of three things:

(1) A preponderance of side area above the center of gravity
(2) Dihedral in the wing

(3) Sweepback of the wing

The best way to illustrate the first effect is to recall the old fashioned flying boats. To balance the large side area of the hull, it was customary to place large fins above the wing. After the side slip began, the side forces on these fins produced a righting moment.

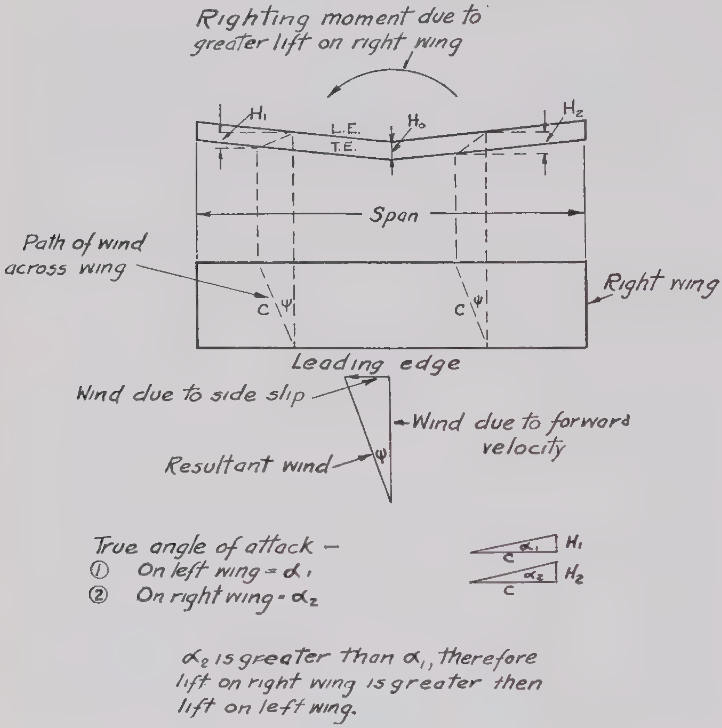
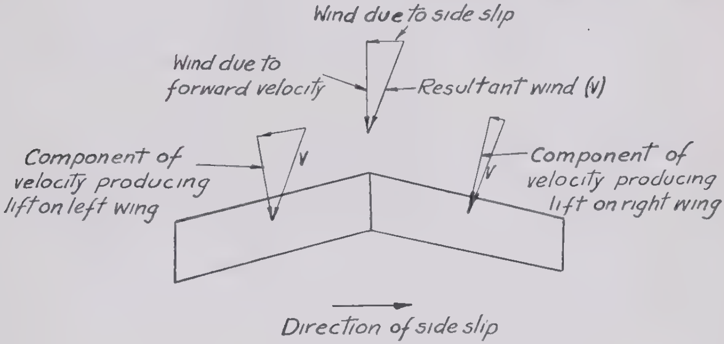


FIGURE 119

Such fins have now been discarded, because they had to be quite large to be effective, and therefore introduced an appreciable drag.

Wind tunnel experiments and theory both indicate that a

dihedral in the wing can give a more powerful restoring moment on a side slip with less loss in aerodynamic efficiency than the wing fins. The wing with dihedral on the side slip experiences a side force just like the fins, and if the wing is above the center of gravity, there is a restoring moment accordingly. This, however, is only a small proportion of the dihedral effect. The major effect comes from the fact that the angle of incidence on part of the wing nearer to the side slip becomes greater than the angle of incidence on the part of the wing farther from the side slip. The diagram of Figure 119 demon-



Lift producing component of velocity is greater on right wing then on left; plane has righting moment in the same direction as given by dihedral

FIGURE 120

strates this effect geometrically. If the wing slips to the right, the air no longer meets the wing symmetrically, but on a line inclined to the axis of symmetry. If a section is taken on the right side, the effective angle of incidence is seen to be increased, while on the left side is decreased.

Sweepback also gives a restoring moment on the side slip but a much less powerful one than the dihedral (1 degree dihedral is equivalent to 10 degrees of sweepback). The effect

of sweepback in a side slip is shown geometrically in Figure 120.

The lift on a wing is really produced by that component of the velocity which is perpendicular to the line of symmetry of its length. On the right wing the side slip brings the resultant wind almost exactly at 90 degrees to this line of symmetry. On the left wing, the resultant wind is still farther away from being at 90 degrees to the line of symmetry.

It is very difficult to calculate the dihedral angle required on a given airplane, because all parts of the machine, struts, wheels, fuselage, etc., contribute to the lateral area and the effects of these various parts are doubtful. Wind tunnel tests are the only reliable guide.

Stability in Yaw

When the airplane swings to right or left from the course, it is said to be yawing from the course.

If a side gust strikes an airplane, it should yaw into the wind like a weathercock. As soon as the airplane is pointed into the gust, the condition of flight becomes absolutely normal. If the airplane swung away from the gust, the abnormality of the flight condition would be increased and might result in a spin.

In order that an airplane may have weathercock stability, it should have a preponderance of lateral area behind the center of gravity. Figure 121 illustrates this point. The resultant wind is composed of the wind of forward motion of the airplane and of the side gust. If there is a large vertical fin surface at the rear of the airplane, the nose of the airplane will swing to the right into the gust.

It is just as difficult to calculate the amount of vertical fin area required as it is to calculate the dihedral angle required, because again every part of the airplane contributes to the side area. A well streamlined rounded fuselage tapering to a sharp point is in itself a very unstable body from a "weathercock" point of view and larger vertical fin surfaces will be required than for a slab-sided, rectangular fuselage which has

deep sides up to the rudder post (as in Fokker Airplanes for example). Again in a twin-engined airplane with a large cabin fuselage, with rectangular sides projecting well beyond the wings, the forward side area of the fuselage must be balanced by a larger vertical fin area!

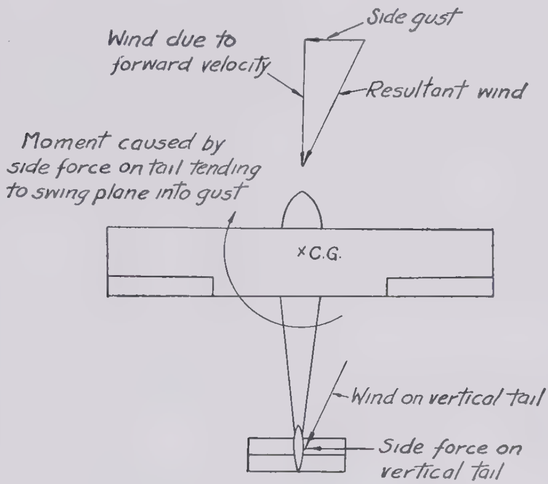


FIGURE 121

Side Slip, Yaw and Side Gusts Equivalent in Their Effects

If a plane side slips to the right, the wind strikes it from the right.

If a machine yaws its nose to the left and continues in its straight line motion, the wind again strikes it from the right.

If a gust coming from the right strikes the plane, the effect is that of the two previous cases.

Side slip, yawing from the course and side gusts may be said to be aerodynamically equivalent therefore. Their effect on the motion are the same and they have to be met by the same aerodynamic stabilizing devices.

Damping of Roll and Autorotation

We have seen that a wing in simple roll, without side slip produces no restoring moment. At the same time rolling motion is opposed by the wing. This is illustrated in Figure 122. That half of the wing which is going down receives the wind due to rolling motion from below and therefore its angle of

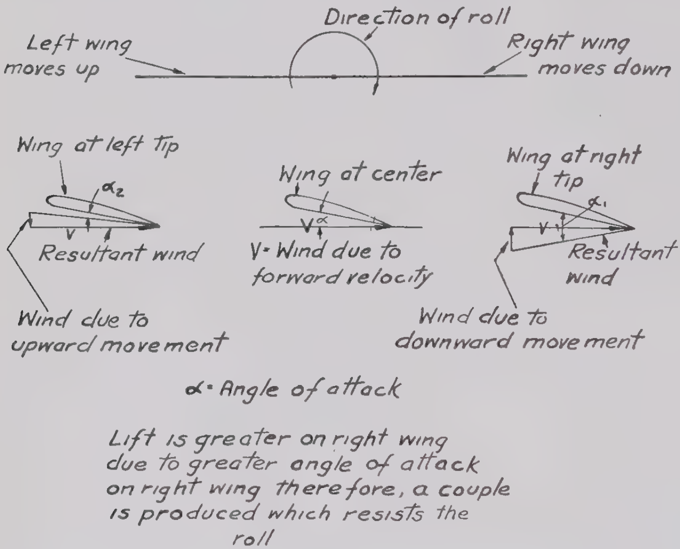


FIGURE 122

incidence is increased, and its lift is likewise increased. That half of the wing which is going up receives the wind due to rolling motion from above and therefore its angle of incidence is decreased and its lift is likewise decreased. The increase in lift on one part of the wing and decrease on the other creates a couple which impedes the roll.

There exists damping of the rolling motion only below the stall however. At the stall that part of the wing for which the angle of incidence is increasing is having its lift decreased,

and the rising part of the wing, conversely, is having its lift increased. Therefore beyond the stall, a wing set in rolling motion will continue to roll, undamped. This phenomenon, known as "autorotation" constitutes a serious danger as it leads to the spin.

What Is Required for Perfect Lateral Stability

For perfect lateral stability we require

1. Ample dihedral effect, so that for a side slip to the right, the right wing tip tends to rise.

2. Ample weathercock effect so that a machine always turns into a side gust.

and also

3. A certain ratio between the power of these two effects.

We do not propose to go into an intricate mathematical presentation of the subject, but the student may find it interesting to follow through a few possible cases of lateral motions (during which the pilot is not supposed to intervene):

Example 1: An airplane with no dihedral in the wing and very large vertical tail surfaces is struck by a gust of wind coming from the right. What sort of motion is likely to follow if the pilot does not intervene?

Owing to the large vertical tail surfaces, the plane will turn rather sharply into the wind. While it is turning the left wing tip will be moving more rapidly than the right tip, and will accordingly tend to rise and the wing will bank. The bank will cause a side slip to the right. The side slip to the right is equivalent to a gust from the right, therefore, the powerful vertical tail surfaces will nose the machine still more to the right. Owing to the natural banking moment, the bank will now be accentuated, followed by more side slip and tighter turning. When the bank has become fairly steep, the vertical tail surfaces will be turning the machine about the horizontal as well as the vertical axis. Finally a tight spiral nose dive will result.

Example 2: A machine with large dihedral in the wing and small vertical tail surfaces is struck by a gust of wind coming

from the right. What sort of motion is likely to follow if the pilot does not intervene?

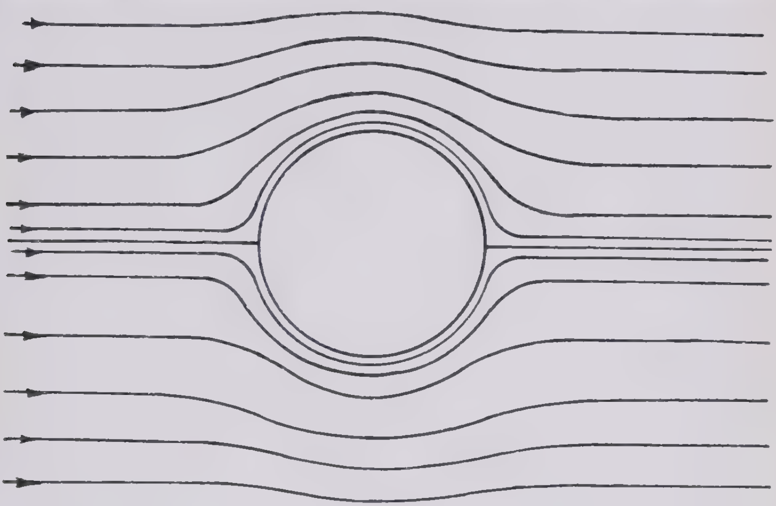
The gust from the right is the equivalent of a side slip to the right. The vertical tail surfaces will turn the nose of the plane to the right. At the same time the large dihedral and the wind from the right will raise the right wing tip rather sharply. The plane will thereafter side slip to the left, start turning its nose to the left, and owing to the large dihedral bank in the opposite direction. An airplane of this description will side slip from side to side, bank one way and then the other, and turn its nose first left and then right. This peculiar oscillating motion is sometimes termed the "Dutch Roll" from a fancied analogy to a certain step in skating.

It is probably safer to build a machine with excess dihedral than with excess of vertical tail surfaces, but the wiser plan is to have both ample dihedral and ample vertical tail surfaces with a reasonable ratio between the two.

CHAPTER XV

MODERN AIRFOIL THEORY

Lanchester in England and Prandtl in Germany have evolved what is known as the Vortex Theory of the Airfoil, which has advanced tremendously our understanding of aerodynamic



Stationary cylinder in perfect fluid

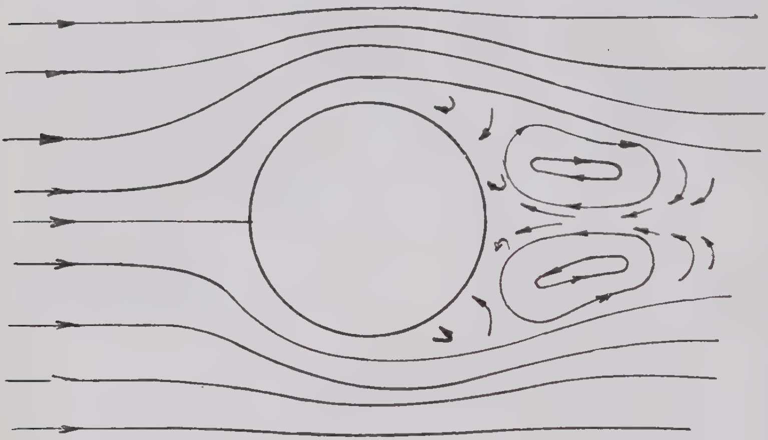
FIGURE 123

phenomena. It is quite possible to understand the general theory of the airplane and even to design aircraft without a knowledge of this theory. Yet the vortex theory opens up

such a new vistas that our readers will be well repaid by an elementary study of this theory.

Why a Rotating Cylinder Lifts

The mathematicians have a conception of a perfect fluid, that is a fluid which has no viscosity. In such a perfect, non-viscous fluid all bodies are perfectly streamline and experience no resistance to motion.



Stationary cylinder in viscous fluid

FIGURE 124

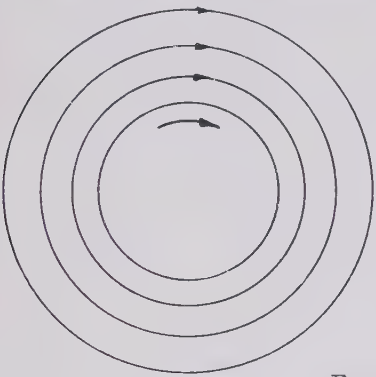
The value of this conception of a perfect fluid is that the flow in such a fluid is easily calculated for simple bodies, and at least approximates the flow in an imperfect fluid such as air or water.

Thus mathematicians can calculate the character of the flow round a cylinder, which is shown in Fig. 123. The flow is per-

fectly symmetrical below and above the cylinder, as we would expect it to be.

In an imperfect fluid the flow round the cylinder is of the character shown in Fig. 124. The fluid gradually retarded by friction of the surface, tears away from the surface and forms the eddies we show in this diagram.

If a cylinder is simply rotated in an imperfect fluid, the fluid is set into rotation or circulation as shown in Fig. 125. A pebble thrown into a pool causes a wave motion or ripples which



Cylinder in perfect fluid with rotation alone.

FIGURE 125

extend to the furthermost confines of the pool. So when the cylinder is rotated, the fluid is set into rotation not only at the surface of the fluid but throughout space, though the fluid moves much more slowly far away from the cylinder.

Now suppose we have fluid flowing past a cylinder and the cylinder rotating at the same time. The rotation of the fluid speeds up the flow above the cylinder, and retards it below.

The combination of the flows of Fig. 123 and of Fig. 125 therefore results in a flow such as that shown in Fig. 126. The fluid above the cylinder flows faster and on a more distorted path.

Now we learned in an early chapter that where the flow is rapid, the pressure is low and vice-versa. Therefore in the

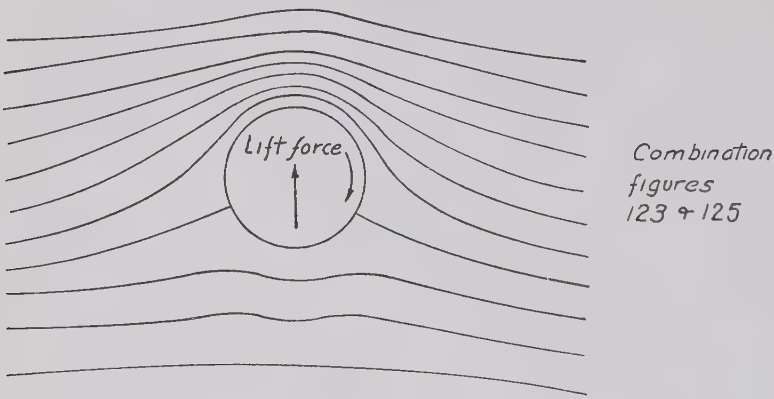


FIGURE 126

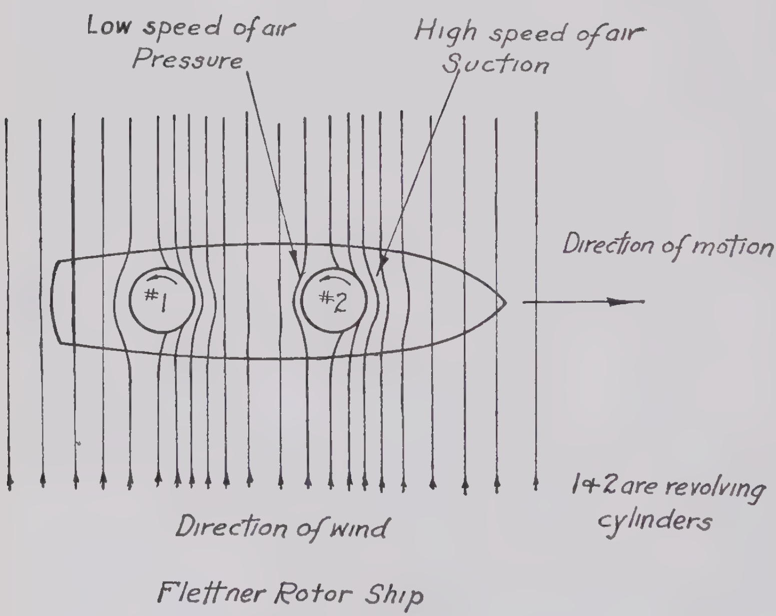


FIGURE 127

cylinder of Fig. 126, there is a region of suction above and a region of pressure below. Accordingly the cylinder experiences a lift force in the direction shown.

The fact that a cylinder rotating in a stream of air exercises lift is the explanation of many phenomena.

Flettner's famous rotor ship was based on this principle. Two large rotors were rotated by electric motors and with the wind abeam a powerful propulsive force was obtained. Flettner's Rotor Ship is shown diagramatically in Fig. 127.

A baseball may be given a special "curve" by an appropriate spin about some axis.

A golf ball may be made to have a short, very high trajectory by striking it above mid axis.

Circulation Theory of Airfoil Lift

The flow round a typical airfoil, in a perfect fluid, would be like that shown in Fig. 128. Of course, there is no perfect fluid, and such a flow round an airfoil could only occur at exceedingly low speeds. We can imagine that at the very start

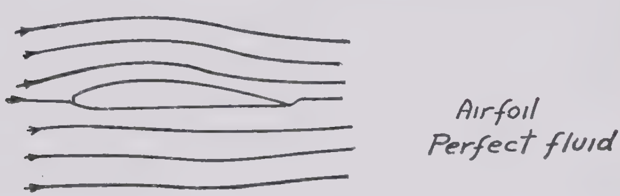


FIGURE 128

of the motion of an airfoil such a flow occurs for a very brief instant. The reason that this flow cannot persist is because the air has to go round a sharp corner at the trailing edge. To go round such a sharp corner it has to go very fast indeed, and owing to the viscosity of the air, it starts dragging the adjacent particles of air with it and forming a vortex at the trailing edge. By a species of internal gearing, the formation

of the vortex at the trailing edge is accompanied by circulation or rotation of the air round the wing. (Fig. 129.)

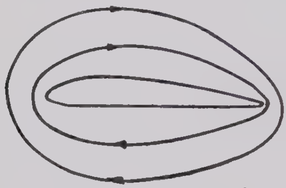


FIGURE 129

The combination of the flow of Fig. 128, with the circulatory flow of Fig. 129, gives the resultant streamline flow of Fig. 130. The circulation round the wing, speeds up the air above it, and produces suction; slows down the air below and produces pressure under the wing. Accordingly lift is produced by circulation just as in the case of the lifting cylinder.

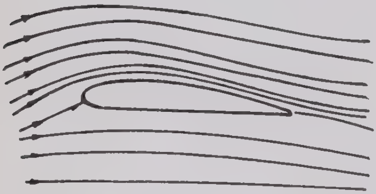


FIGURE 130

It can be shown by fairly simple mathematics (though beyond the scope of this book) that the lift of a wing is proportional to

(a) The density of the air
(b) The velocity
(c) The length of the wing
(d) The intensity of the circulation round the wing.

Tip Vortices

It has been definitely established both by theory and by wind tunnel experiments that certain vortices are produced towards

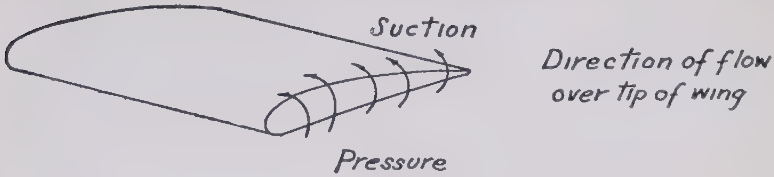


FIGURE 131

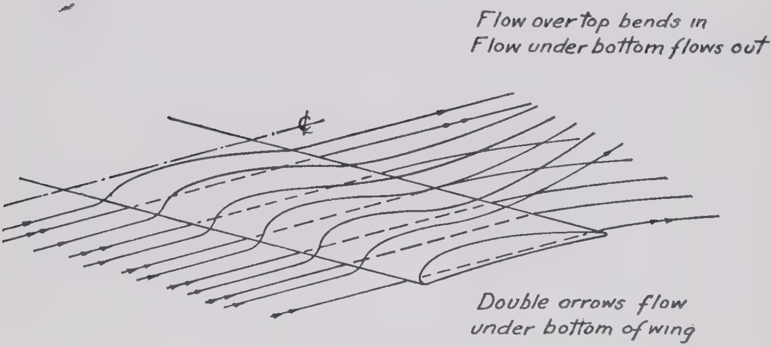


FIGURE 132

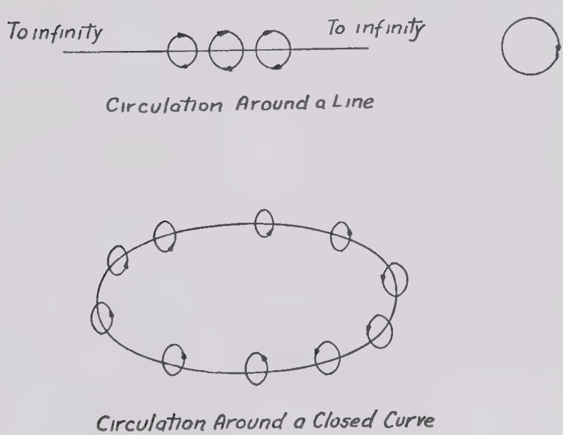


FIGURE 133

the tip of the wing. Let us study the diagrams of Fig. 131 and 132. Since there is pressure below the wing and suction above it, there must be an end flow, as shown, from below the wing to its upper surface. This end flow is superimposed on the general flow past the airfoil, so that at the trailing edge the

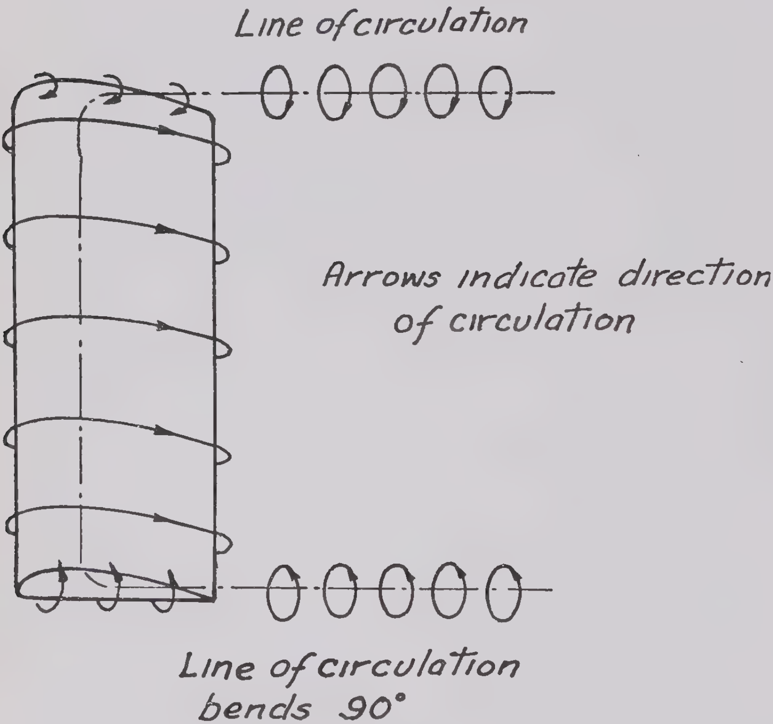


FIGURE 134

air above the wing flows partly towards the center of the wing, and the air below flows partly away from the center of the wing. Hence an eddy or vortex is formed which trails behind the wing as shown in Fig. 133.

Another Way of Explaining Tip Vortices

Lord Kelvin has shown that if there is circulation round a line, either the line is closed on itself or else its two ends extend to infinity. This idea is illustrated by Fig. 134.

Now consider that imaginary line in the wing, which is the center of the circulation.

Beyond the ends of the wing, there is no lift and therefore no circulation. Therefore in accordance with Lord Kelvin's law, the central line of circulation must at the wing tips, bend at 90 degrees and produce tip vortices as in Fig. 133.

We have thus demonstrated the existence of tip vortices by two independent methods.

Vortices Really Leave Rear of Wing All Along Its Span

With a wing of exactly the same cross-section or profile all along its span, it might be expected that the lift per unit length of span would be the same all along the span. In actual fact, the lift falls off rapidly at the tips, much in the way indicated

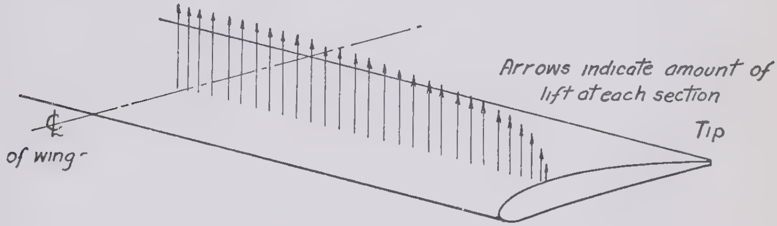


FIGURE 135

in Fig. 135. Wherever there is a decrease of lift, there is also a decrease in circulation, and since circulation cannot be destroyed, vortices pass off from the trailing edge of the wing all along its length as shown in Fig. 136. These vortices or vortex filaments attract each other and roll up into a sort of rope (Fig. 137) towards either wing tip. It is therefore quite proper in elementary theory to calculate as if we had a single tip vortex at either end of the wing.

Tip Vortices Produce Induced Drag

Let us study again the diagram of Fig. 133. At the wing itself, the tip vortices evidently produce or induce a downward velocity. If this velocity is compounded with the horizontal

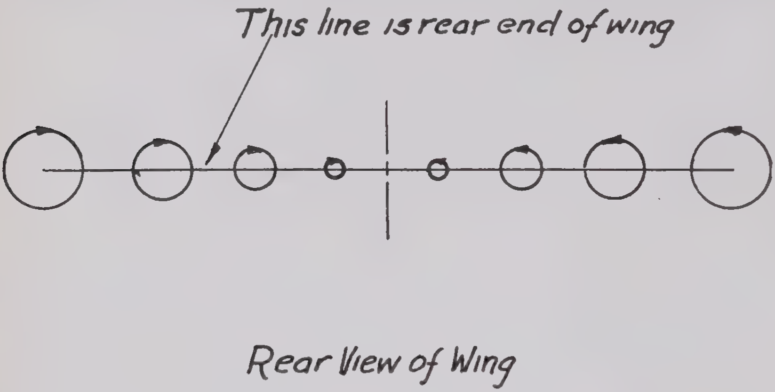


FIGURE 136

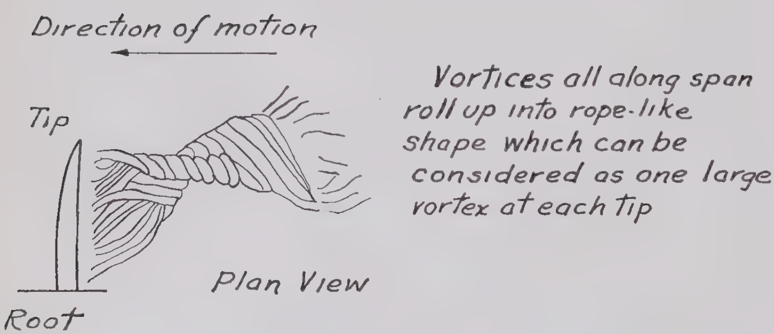


FIGURE 137

velocity of forward motion, the resultant velocity of the air striking the wing is downward. Since the lift is always at right angles to the resultant wind, the lift on the wing is now not quite vertical. As in Fig. 138, a certain part of the lift is now acting backwards, and producing drag.

This drag is termed the induced drag of the wing.

The greater the lift coefficient at which a wing is working, the greater is the tip vortex effect, and the down wash at the wing. Since at the same time the lift force is greater, it follows that the induced drag is proportional to the square of the lift coefficient.

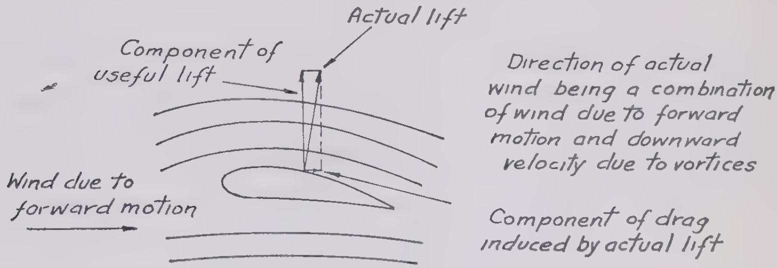


FIGURE 138

Again the greater the aspect ratio, the less is the effect of the tip vortices.

These considerations can be put into one concise equation

$$Kx_i = \frac{125\ K_y^2}{A.\ R.}$$

whose Kx_i = coefficient of induced drag

K_y = lift coefficient

A. R. = aspect ratio.

If a wing is of infinite length, the center line of circulation also extends to infinity and there are no end losses, no tip vortices, no downward velocity at the wing and no induced drag.

A wing of infinite span has no induced drag therefore.

A wing of infinite span will nevertheless have a drag (mainly due to skin friction or rubbing of the air over its surface) which is termed profile drag. Since this profile drag is dependent on skin friction alone, it will not be affected by the lift coefficient nor by the aspect ratio, and will be substantially constant at all angles of incidence.

We can now write

$$K_x = \text{induced drag} + \text{profile drag.}$$
$$= Kx_i + Kx_p$$
$$= \frac{125\ K_y^2}{\text{A. R.}} + Kx_p.$$

Aspect Ratio Effects in the Light of the Vortex Theory

Our reader may have found all this discussion of vortex theory very abstract and somewhat difficult. He will be rewarded

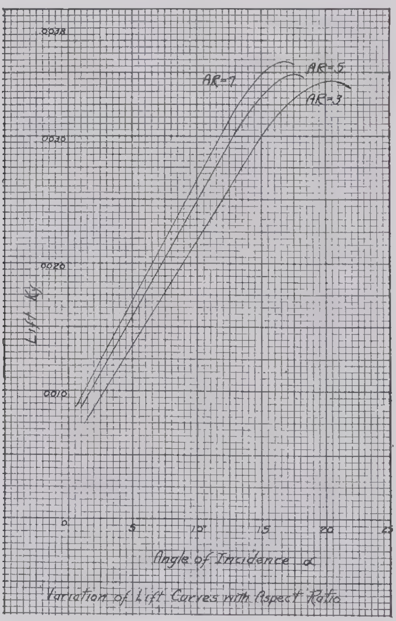


FIGURE 139

by the light which the theory throws on the practical aerodynamics of the airplane. For example, the vortex theory ex-

plains adequately the effects of aspect ratio, the ratio of span to cord, of the wing on its aerodynamic properties.

With increased aspect ratio the induced drag $\dfrac{125\ K_y^2}{A.\ R.}$ will decrease for a given lift coefficient.

Of two wings with a given profile, but different aspect ratios,

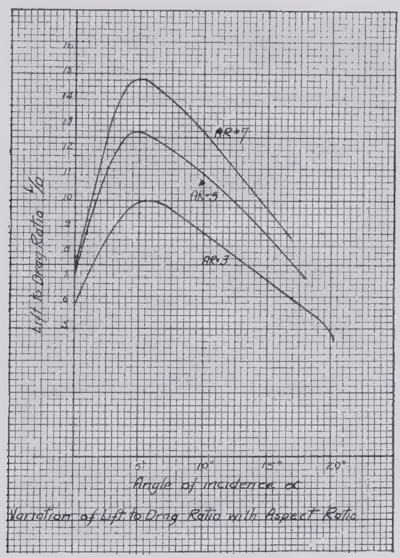


FIGURE 140

the wing with greater aspect ratio will therefore be more efficient.

If a wing is working at a low value of K_y, the induced drag is small, and the aspect ratio is of little importance. Hence for a racing machine, low aspect ratio may be employed without hurting the top speed.

When cruising or climb is important, then we must have

efficiency at a fairly high value of the K_y or lift coefficient. Therefore we must keep down the induced drag $\dfrac{125\ K_y^2}{\text{A. R.}}$ and employ a large aspect ratio.

Again if the aspect ratio is high, the downwash at the center of the wing is smaller than for a wing of low aspect ratio working at the same angle of incidence. Therefore for the same angle of incidence, the lift of the high aspect ratio wing should be higher than the lift of the low aspect ratio wing. As we have stated in a previous article, that is why tail surfaces of large aspect ratio are advantageous.

In Fig. 139, we have plotted curves of lift against angle of incidence for the same wing with different aspect ratios, and in Fig. 140, curves of lift over drag, both for a typical wing section and both derived from wind tunnel experiments. It can be seen that experimentation fully confirms our theory.

Examples

The L/D of the Clark Y is 20 at 0 degrees incidence for aspect ratio 6 and the K_y at this incidence is .0010. What is the induced drag coefficient? What is the profile drag coefficient?

The induced drag is given by the formula

$$\frac{125\ K_y^2}{\text{A. R.}} = \frac{125\ (.0010)^2}{6} = .0000208$$

The drag coefficient $= \dfrac{K_y}{L/D} = \dfrac{.0010}{20} = .000050$

Therefore the profile drag $= .00005 - .0000208 = .0000292$ which is slightly less than the minimum drag coefficient of .000035.

Example

What will be the L/D of the Clark Y wing at $K_y = .0010$ for an aspect ratio of 9?

The profile drag coefficient is .0000292, as calculated in the previous example.

The induced drag coefficient is

$$\frac{125\ K_y^2}{\text{A. R.}} = \frac{125\ (.0010)^2}{9} = .0000139$$

The total drag coefficient = .0000292 + .0000139 = .0000431

and the L/D is now $\dfrac{.00100}{.0000431} = 23.2$ as compared with the 20 for aspect ratio 6.

Problems

1. A plane of 200 square foot wing area loaded to 10 pounds per square foot and having a span of 40 feet is flying at 100 miles per hour. What is the induced drag? What is the horsepower required to overcome the induced drag?

2. The lift/drag ratio of a wing of aspect ratio 6, is 18 at $Ky = .0010$. What is the induced drag coefficient? What is the profile drag? What is the L/D of the same wing at an aspect ratio 10?

Answers

1. Induced drag = 31.2
   H.P. to overcome induced drag = 8.3.
2. $Kx_i = .0000208$
   $KP = .0000347$
   $L/D = 21.2.$

CHAPTER XVI

SELECTION OF AIRFOILS

Desirable Characteristics of an Airfoil

In spite of the hundreds, perhaps thousands of airfoils tested in the various aerodynamic laboratories of the United States and Europe, no "best" airfoil has been discovered. Some airfoils are better from one point of view, some from another. For a given airplane design, however, there are generally some two or three airfoils to be found which fit the particular problem best.

We will first of all classify the various airfoil characteristics which are desirable.

1. *A Low Value of the Minimum Drag.* This is very important for high speed machines, which fly at small angles of incidence at or near the condition of minimum drag. We have seen in a previous article that horse-power required $= \dfrac{K_x AV^3}{375}$.

If K_x is small it is therefore possible to get a higher speed with a given power, or to call for less power with a given speed.

2. *A High Value of Maximum Lift Coefficient.* The stalling or minimum speed is given by the formula $V = \sqrt{\dfrac{W}{K_y \text{ max. } A}}$

Hence a high value of the maximum K_y will give a lower landing speed, or with a given landing speed allow the use of more loading per square foot, giving a smaller, more compact and lighter airplane.

3. *A High Ratio of Maximum K_y to Minimum Drag.* One of the principal requirements of airplane design is a good value

of speed range, that is maximum speed divided by minimum speed. Since high maximum K_y tends to low landing speed, and low minimum K_x means good high speed, it is clear that a high ratio $\frac{K_y \text{ maximum}}{K_x \text{ minimum}}$ is an indication of good speed range.

4. *A High Value of Maximum Lift/Drag.* Machines are not generally loaded enough per square foot to fly at the angle of best Lift/drag at cruising speed. Nevertheless a high value of maximum L/D is a good indication of cruising efficiency. For a commercial airplane which is to fly cross-country at cruising speed, high maximum L/D is probably more important than a very low value of minimum drag.

5. *A High Value of Lift/Drag at Climbing Angles.* An airplane generally climbs best at a fairly high angle of incidence, between 8 and 10 degrees incidence. As a rule in commercial airplanes, the climb is quite satisfactory. Nevertheless a thorough analysis of an airfoil should include a consideration of the L/D at climbing angles. Perhaps a better way of picking a climbing wing is to consider what is known as the power coefficient rather than to pick L/Ds at random in the region of climb. The power coefficient is obtained as follows:

$$\text{Wing Thrust} = \frac{\text{Weight}}{\begin{array}{c}\text{Lift/Drag}\\ \text{of wing}\end{array}} = \frac{W}{L/D} = \frac{W}{\dfrac{K_y}{K_x}}$$

$$\text{Wing horse-power required} = \frac{\text{Thrust x V (miles per hour)}}{375.}$$

$$\text{But } V = \sqrt{\frac{W}{K_y A}}$$

$$\text{Therefore horse-power required} = \frac{W}{K_y/K_x} \cdot \sqrt{\frac{W}{K_y A}}$$

$$= \frac{W\sqrt{W}}{\sqrt{A}} \cdot \frac{1}{\frac{K_y\sqrt{K_y}}{K_x}}$$

as can be readily determined by using a little algebra.

With fixed weight and area, the horse-power with the plane flying at any K_y will therefore depend on the value of

$$\frac{1}{\frac{K_y\sqrt{K_y}}{K_x}} \text{ or } \frac{1}{\frac{K_y^{1.5}}{K_x}}$$

When the wing horse-power is the smallest possible, $\frac{K_y^{3/2}}{K_x}$ must have its maximum value.

But an airplane climbs best when the wing horse-power is approximately at its lowest value, because there is then a maximum of excess power to overcome gravity.

Therefore, the airplane will climb best when its $\frac{K_y^{3/2}}{K_x}$ is at its maximum value.

For climb, that airfoil will be best which has the highest maximum value of $\frac{K_y^{3/2}}{K_x}$.

6. *Small Center of Pressure Travel.* We have seen in previous articles that the ordinary conventional wing has an unstable center of pressure travel. When the wing noses down, the cen-

ter of pressure travels back and increases the nosing down tendency. When the wing noses up, the center of pressure travels forwards and increases the nosing up tendency. Hence from a stability point of view, it is desirable to have as small a center of pressure travel as possible. By a slight turning up of the rear part of the airfoil it is even possible to obtain a constant center of pressure. There is also another advantage in a small center of pressure travel, and that from the structural point of view. When the center of pressure travels forward it is the front spar that is bearing the major part of the wing load. When the center of pressure travels back, the rear spar has to withstand the greater strain. With a small c.p. movement the loads can be concentrated more on one spar, and the wing made lighter accordingly.

7. *Depth of Spar.* If we take a flat ruler, and hold it flat, it is quite easily broken. The same ruler held on edge will not be readily broken by the strongest fingers. A beam to be strong should be narrow and deep. From a structural point of view, therefore, that airfoil will be best, which allows of the design of deep spar, both front and rear.

What Is a Desirable Wing Profile?

So many airfoils have been developed, tested and studied that it is impossible for us to consider even a small proportion of them in detail.

Speaking generally, an airfoil should have:

1. A generally pleasing, streamline appearance, with no very abrupt changes of curvature anywhere, no gaps or breaks on upper or lower surface.

2. A nicely rounded front nose, and a sharp trailing edge, or a trailing edge coming to a rounded point of very small curvature.

3. A maximum thickness at about one-third of the chord from the leading edge.

4. Neither excessive upper camber, since this may mean excessive drag with no compensating increase in lift,

5. nor excessive hollowing out of the under surface, since

this may mean excessive drag not compensated for by the increase in lift, and also reduction of the spar depth available,

6. nor excessive camber below the chord line, since this will decrease the lift, even though minimum drag may be diminished thereby.

These geometric considerations are illustrated in Fig. 141.

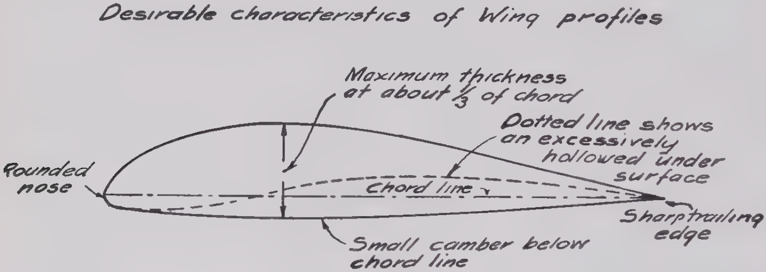


FIGURE 141

What Theory Teaches Us About Wing Profile

In recent years, Hydrodynamics, the theory of fluid flow has been very successfully applied to the study of the airfoil. It is impossible without an extensive knowledge of mathematics to appreciate this theory. It is however possible to take the findings of modern theory, to see if it corresponds with common sense, and to use its results for the appreciation of wing profiles.

The first thing that Hydrodynamic theory teaches us is that the characteristics of an airfoil depend above all else on the mean camber line. The mean camber line is illustrated in Fig. 142. It is obtained by taking the mean of the ordinates of the upper and lower surface of the airfoil. The camber of an airfoil is defined by the ration of maximum camber to chord.

Another way, though only approximate of defining the mean camber is to join the mid-point on the mean camber line to the trailing edge. The angle between this line and the chord may be termed the mean camber angle; the chord is defined as the line between the extreme leading edge and the trailing edge.

It is illustrated in Fig. 143. This angle is generally denoted by the symbol β.

We have seen previously that when the chord is at zero the lift is not necessarily zero. The lift is zero however when the

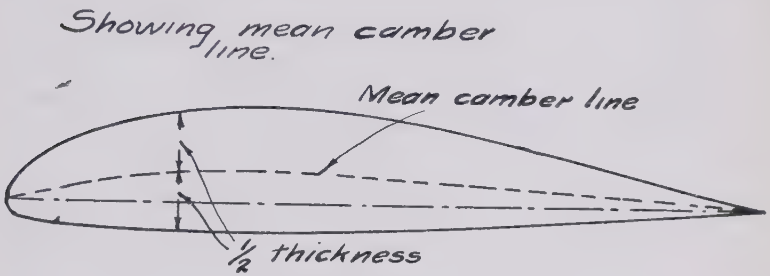


FIGURE 142

wind strikes the airfoil along this line from the trailing edge to the mid-point on the mean camber line. This line may therefore be termed the line of no lift, and it makes an angle β with the chord line.

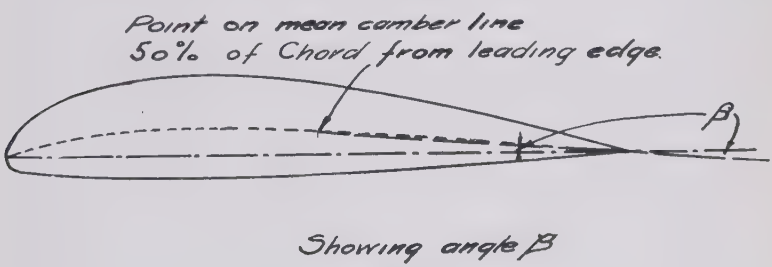


FIGURE 143

As the mean camber increases, so does the value of the angle β. This is illustrated in Fig. 144. For the symmetrical, double cambered profile shown in this diagram, the angle β is evidently zero. And when the chord line of the double cambered surface is at zero, the lift is zero also. For the thin air-

foil, of small mean camber, β has a value of something like 4 degrees, and the lift is zero when the chord is at -4 degrees accordingly. For the thick, heavily cambered airfoil, the angle β is 6 degrees and the chord must be at -6 degrees before the lift disappears.

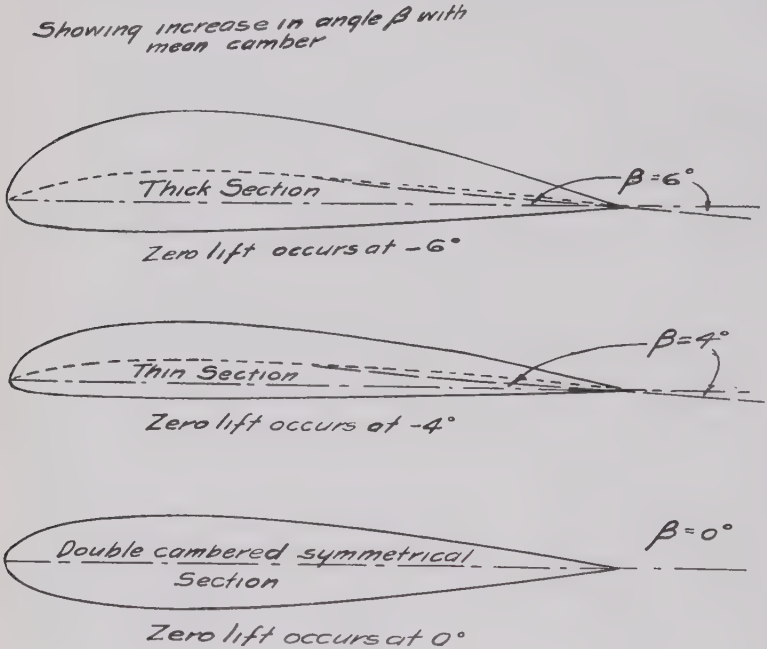


FIGURE 144

There is another very interesting fact to be learned from this Fig. 141, and that is that the lift curve of the airfoil when plotted against angle of incidence always has approximately the same slope.

If we know the value of this slope, we can calculate the lift coefficient for any angle of incidence. From wind tunnel tests for wings of aspect ratio 6, it has been found that this slope is approximately .000184 K_y per degree.

Suppose that we want to calculate the lift of an airfoil of camber angle β of 6 degrees, when the angle of the chord is 4 degrees. The wing is then at 6 + 4 degrees from the angle of no lift. The K_y is therefore 10 multiplied by .000184 or .00184.

The reader may ask how the mean camber angle is related to the maximum lift coefficient.

All airfoils reach their maximum lift at approximately the same angle of incidence of the chord. But the thick heavily cambered wings started lifting at a bigger negative angle. The range of the angles from zero lift to maximum lift is therefore larger, and with the same slope, the maximum lift is larger.

This camber angle β also serves to indicate the center of pressure motion.

The position of the center of pressure is given approximately by the formula $C.P. = \dfrac{\beta}{14100\ K_y} + \dfrac{1}{4}$. So the greater the value of β the greater is the travel of the center of pressure.

The greater the mean camber and the greater the thickness of the wing, the greater also the minimum drag.

We have to pay for increased lift, obtainable by greater mean camber, therefore by a greater movement of the center of pressure and by greater drag. Nevertheless the designer may select the wing of greater mean camber for other reasons, such as low landing speed and greater spar depth.

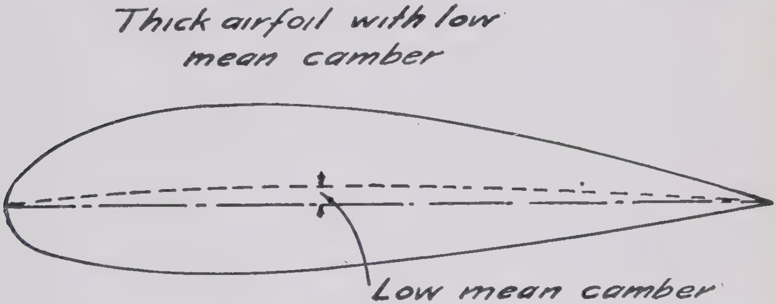


FIGURE 145

There is one more point to make clear. The wing may have great thickness, yet low mean camber. This is illustrated in Fig. 145 where the wing has a convex camber on the lower surface, and a low mean camber, though it is very thick.

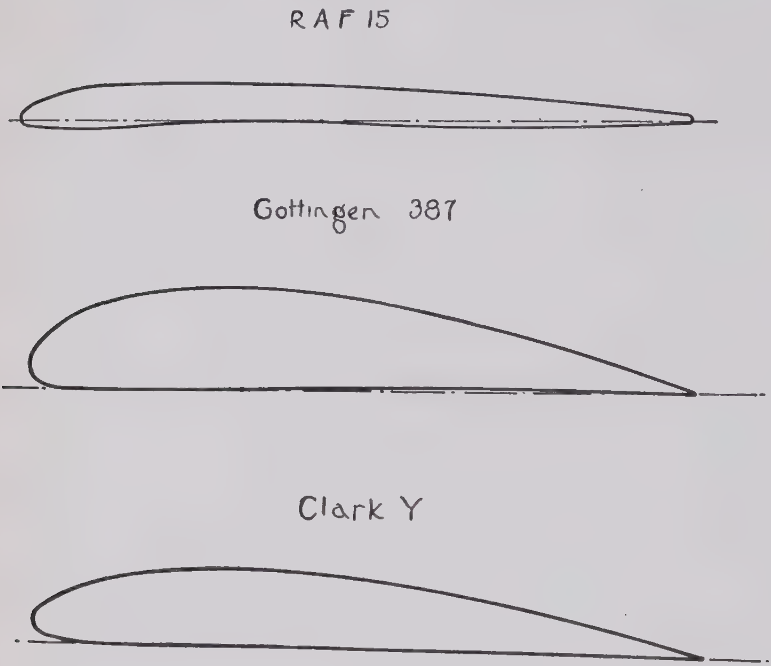


FIGURE 146

Where a designer needs great spar depth, as at the root of an internally braced cantilever wing, it is possible to keep the mean camber within reasonable limits, yet to secure the spar depth by using a convex camber on the lower surface. This is a very useful aerodynamic dodge.

There is still another very useful property of the airfoil. By turning up the rear trailing edge, it is possible to reduce the

center of pressure motion very much. If the turning up of the trailing edge is skilfully done, there is comparatively little loss in maximum lift and little increase in minimum drag.

Analysis of Some Typical Airfoils

In Fig. 146 are shown some typical and frequently used airfoils, the R.A.F. 15, Clark Y and Gottingen 387, and in Figs. 147, 148 and 149 are shown their characteristics.

In Table 1 the characteristics of these airfoils have been tabulated.

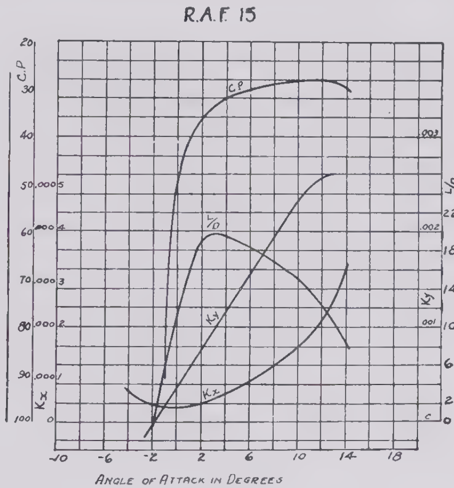


FIGURE 147

The table includes: 1. The maximum camber of the upper surface as a percentage of the chord. 2. The maximum camber of the lower surface as a percentage of the chord. 3. The position of the maximum camber and its magnitude as a percentage of the chord. 4. The maximum thickness of the airfoil as a percentage of the chord. 5. The thickness at 15 per cent of the chord where the front spar is likely to be placed. 6. The thickness at 65 per cent of the chord where the rear

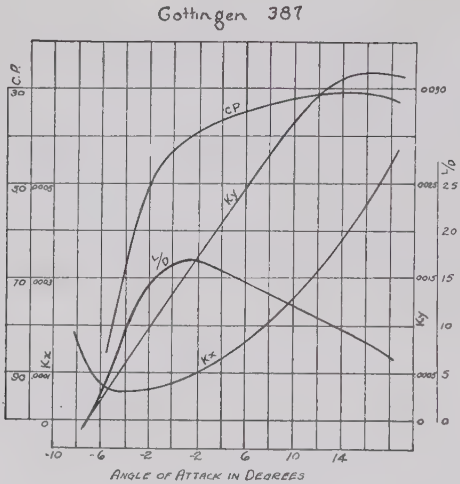


FIGURE 148

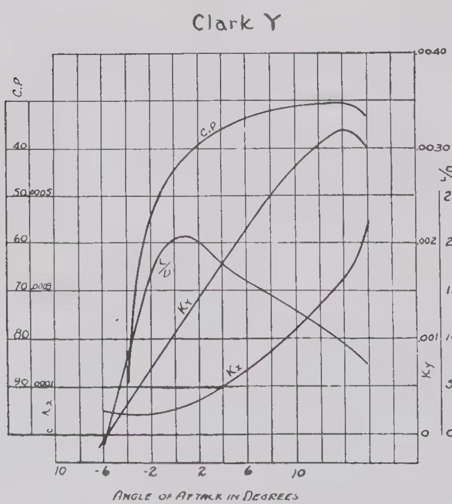


FIGURE 149

Tabulated comparison of airfoils often used.
Aspect Ratio 6
Rectangular plan form.

Wing	R. A. F. 15	Clark "Y"	Gottingen 387
(1) Max. camber of upper surface	5.83%	9.3%	12.7%
(2) Max. camber of lower surface	−1.02%	2.8%	3.2%
(3) Position of max. camber	26.7%	29.8%	30.7%
(4) Max. thickness	6.36%	11.7%	15.1%
(5) Thickness at 15% of chord	6.36%	10.5%	13.83%
(6) Thickness at 65% of chord	4.90%	8.3%	9.89%
(7) Value of Angle B	1.4°	3.1°	5.0°
(8) Angle of no lift	−1.8°	−3.3°	−5.1°
(9) Working range of angles	16.0°	19.5°	23.0°
(10) Slope of lift curve	.000196	.000176	.000163
(11) C. P. travel from $K_{y max}$ to $\frac{K_{y max}}{6.25}$	18%	27	35.5%
(12) Minimum K_x	.000031	.000038	.000060
(13) L/D maximum	19.5	21.0	16.95
(14) $\frac{\text{Max. } K_y}{\text{Min. } K_x}$	86.6	84.2	61
(15) $\left(\frac{K_y^{3/2}}{K_x}\right)$ max.	.73	.76	.73
(16) Maximum K_y	.0026	.0032	.00366
(17) Maximum mean camber	2.30%	3.25%	5.1%

spar is likely to be placed. 7. The value of the angle β. 8. The angle of no lift which is approximately equal to β. 9. The working range of angles, that is between no lift and

maximum lift. 10. The slope of the lift curve, that is the amount by which the angle measured from the line of no lift has to be multiplied by, to give the lift at any incidence. 11. The center of pressure travel from maximum K_y to maximum K_y over 6.25 giving a speed range 2.5. 12. The minimum drag. 13. The best value of the Lift/Drag ratio. 14. The value of the constant Max. Lift/Minimum drag. 15. The best value of the power coefficient K. 16. The maximum K_y. 17. The maximum mean camber.

It is surprising how closely the actual tunnel values come to the theoretical values.

A close comparative study of these three airfoils, will enable the reader to judge for himself of the other airfoil in which he may be interested.

It should be carefully noted that in theoretical considerations of airfoils, the chord should always be drawn from the trailing edge to the extreme leading edge.

Discussion of Tables

From the table of actual airfoils we can draw the following general conclusions:

(1) The lift coefficient and the range of working angles increase with the maximum mean camber.

(2) The center of pressure movement increases with the angle β as theory indicates.

(3) The negative angle of no lift is approximately equal to the angle β.

(4) The slope of the lift curves are in fairly close agreement with the theoretical slope of .000184.

(5) The profile drag (minimum K_x) increases with the maximum mean camber, and with the thickness.

(6) The working range of angles increases with the thickness.

(7) The best value of $\dfrac{K_y\ 3/2}{K_x}$ is about the same for the three airfoils considered.

On the whole theory checks with experimental values fairly well and certainly offers a powerful weapon for predicting the characteristics of a wing.

The three wings listed in the table are all good wings if used in approximate designs. A consideration of the type of ship for which each wing is suitable is given here:

R. A. F. 15

This airfoil, due to the small depth of spar, must certainly be used in conjunction with an externally braced wing. Since the most pronounced features of the airfoil are the low minimum K_x and the low C.P. movement, the wing is very good for a high speed plane in which the major consideration is drag of the airfoil, at small angles of attack.

Clark Y

This airfoil has neither extremely low K_x, high K_y nor very small C.P. movement. However, it has an extremely good value of L/D. It would therefore not be the best for high speed ships, nor for ships desiring a low landing speed. It is, however, very often used on ships which are designed to have good cruising efficiency, that is, a low value of gasoline consumption per mile flown.

Gottingen 387

This section has an advantage from the structural standpoint. That is, it has room for large spars in the wing. Since this is the case, it can be internally braced. It has also a high lift coefficient which means a low landing speed. However, the wing is obviously not good for high speeds due to the high value of the minimum drag coefficient. Therefore, the type of ship on which this airfoil could be used to advantage would be a heavily loaded ship in which load carried was the important factor and high speed was relatively unimportant.

Problems

1. Using the profiles of Fig. 146, draw the true hydrodynamic chords, and compare their positions with the conventional chord.
2. Using the profiles of Fig. 146, draw mean camber lines for each airfoil, and check the values of the angle β.
3. At what angle of incidence measured from the conventional chord is there no lift for these three airfoils?
4. When the line marking β is in line with the wind how close to the experimental zero lift are these airfoils?
5. For all three wings calculate the Ky theoretically when the chord is at 4 degrees incidence.
6. For all three wings calculate theoretically the center of pressure when the hydrodynamic chord is at 4 degrees incidence.
7. If a wing has an aspect ratio of 6 and an angle of β of 4°, what are the following characteristics
   (a) Ky at 0° and 10°
   (b) C.P. position at the above angles.
8. If the wing in problem 7 has a minimum Kx of .00003 what is the L/D at 0° incidence?
9. If the wing of problem 7 has a depth at 15% of chord of 13%, and a depth at 65% of chord of 10%, for what type of ship do you think this wing is best, and why?
10. What would be the H.P. required by the wing in problem 7 if the span were 100 ft., chord 10 ft., and was traveling at a speed of 100 m.p.h., at 2° incidence?

Answers

5. Wing............................Ky at 4° incidence
   R.A.F. 15 00099
   Clark Y 00131
   Gottingen 387 00166
6. Wing ....C. P. at 4° incidence
   R.A.F. 15 ....35%
   Clark Y 41.8%
   Gottingen 387 ....46.3%

7. (a) .00736; .00184; .0026
   (b) 63.5%; 40.2%; 35.9%
8. $L/D = 16.6$
10. 149 H.P.

CHAPTER XVII

THE HANDLEY PAGE SLOT AND OTHER DEVICES TO INCREASE WING LIFT

As we have stated in previous chapters an important problem in modern aviation is to decrease the landing speed, length of landing run, and length of get-away run. These objectives are closely allied and constituted the main purposes of the Guggenheim Safe Aircraft Competition.

If the maximum lift coefficient of a wing is increased, the minimum flying speed is decreased for a given area and gross load, because $V_{landing} = \sqrt{\dfrac{W}{k_{y\,max.} A_{area}}}$.

If the minimum air speed is decreased, then the length of landing run is decreased also, because the airplane has less kinetic energy on landing. Again if the minimum flying speed is less, a shorter run on the ground is required before the airplane gets into the air.

Improvement in all three characteristics, without sacrifice of other good qualities of the airplane, is thus seen to depend mainly on increase in the maximum lift coefficient of the wing.

The maximum lift coefficient of wings as used in practice today rarely exceeds .0036. Wings have been designed and tested in wind tunnels which have maximum lift coefficients of over .0040, in two cases as high as .00456. But such wings of excessively high lift, have also very high drag and poor lift/drag, and are entirely unsuitable for general use.

It does not seem promising therefore to seek wings of very high lift, but rather to use devices which will increase the lift of the wing when required (that is on landing or take-off) but which will not increase the drag of the wing in normal flight.

It is the purpose of this article to review briefly what has been attempted thus far along these lines.

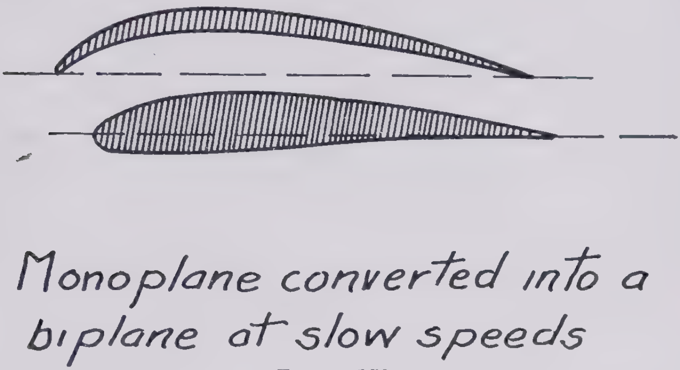


FIGURE 150

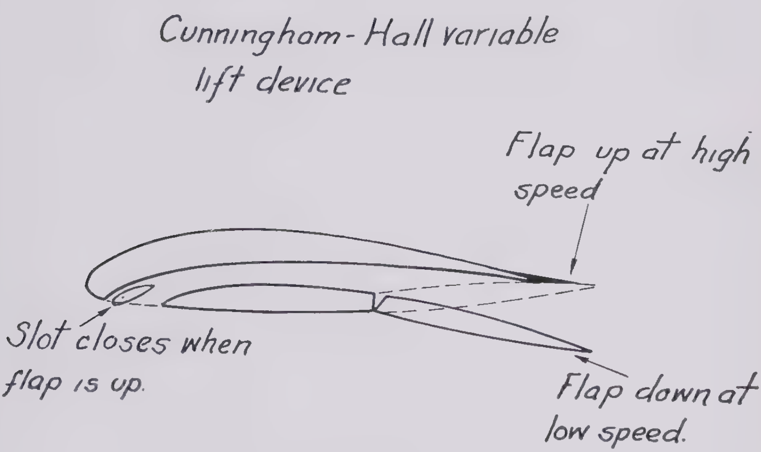


FIGURE 151

Monoplane Converted into Biplane

The arrangement shown in Fig. 150, has been tested in the wind tunnel at Göttingen University. With the upper wing brought down to fit over the lower wing, the combination gave

a conventional wing of good efficiency. With the two surfaces opened up, a maximum k_y of .00605 was obtained, nearly twice the normal value. The conversion of a monoplane into a biplane is also being developed by some competent engineers in the United States. Aerodynamically the idea is promising, but its mechanical execution is not so easy.

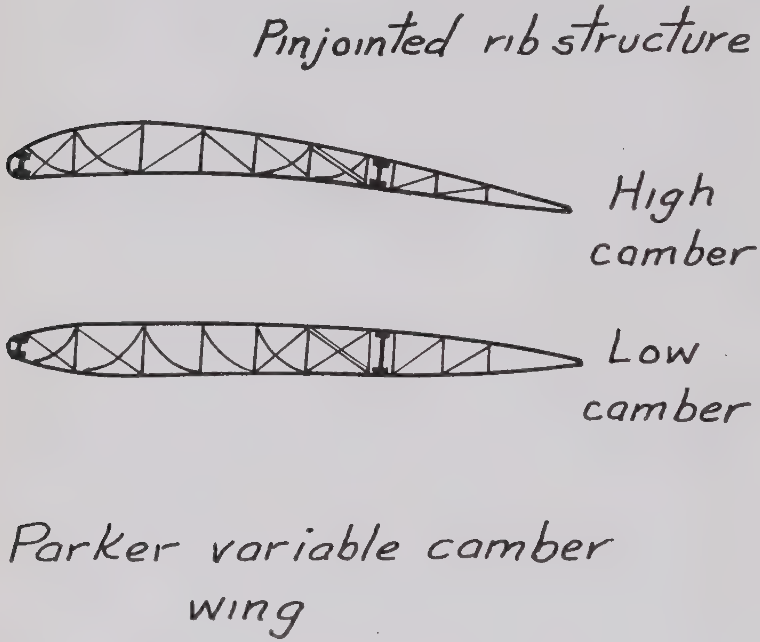


FIGURE 152

R. H. Hall of the Cunningham-Hall Aircraft Corporation has also worked on the conversion of a monoplane into a biplane, but on a different principle. The device is illustrated in Fig. 151. The opening of the front flap and the depression of the rear flap gives the equivalent of a biplane of very small gap. The tunnel tests showed very high increases in maximum k_y values. A machine embodying this device was presented at the Guggenheim Safe Aircraft Competition and the mechanical

functioning of the device presented no difficulty, although owing to insufficient lateral control it was found impossible to test the aircraft at the high angle of incidence necessary to develop its full lift value.

Variable Camber

Quite a number of men have worked on the idea of varying the camber. At high speeds the wing is to be of low camber, high speed profile; at landing it is to be converted into a high lift wing. The Parker and the Burtenbach Variable Camber

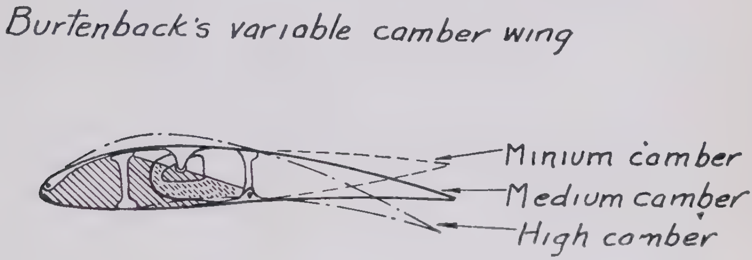


FIGURE 153

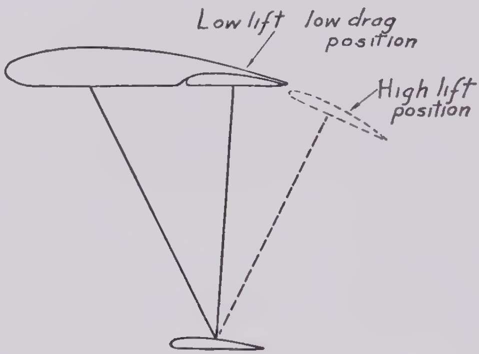
wings are illustrated in Figs. 152 and 153. The objections to such devices are that the increase in lift possible when varying the camber is only moderate. If the camber is increased beyond a certain point, the wing no longer maintains its streamline contour and the increase in lift which might be anticipated is not realized. In view of the small effects produced and the mechanical complication involved, it may safely be said that variable camber wings are not promising.

Variable Area and Camber

A number of machines have been flown, in which both the area and the camber have been changed simultaneously. The principles involved are illustrated in Figs. 154, 155 and 156. In the Gastambide-Levasseur airplane, built and flown in France, a fixed lower wing was combined with a variable area

upper wing, the movable portion of the upper wing pivoting about a hinge fastened in the lower wing. Reports state that quite an appreciable improvement in speed range was obtained.

The principle of Harlan D. Fowler's variable area and camber wing is clear from our sketch. Both in the wind tunnel and in application to Curtiss JN, the device showed considerable improvement in maximum lift.



Gostambide - Lavasseur variable camber and area arrangement

FIGURE 154

At the Guggenheim Safe Aircraft Competition, Burnelli presented a machine in which the rear part of the wing slid back and down, the front part, forwards and down. This in the wing tunnel also gave an appreciable increase in lift.

There is no doubt that the combination of variable camber and area can be made to give an increase in lift of some seventy per cent over the basic wing. It remains to be seen, however whether the principle will be embodied in practice because of the mechanical complications involved.

Variable Incidence

We will only mention the use of variable angle of incidence to warn of its futility as a means of increasing lift. No mat-

ter what angle of incidence a wing may be set to the thrust line or other fixed line of the airplane, its maximum lift coefficient cannot be increased by such variation in setting. There-

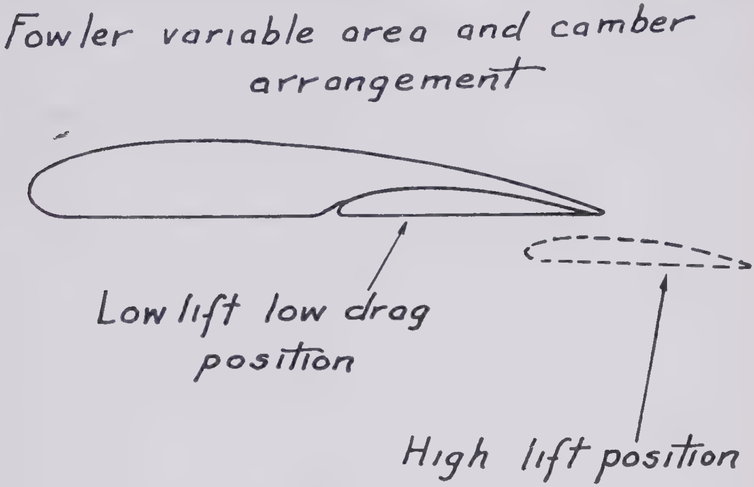


FIGURE 155

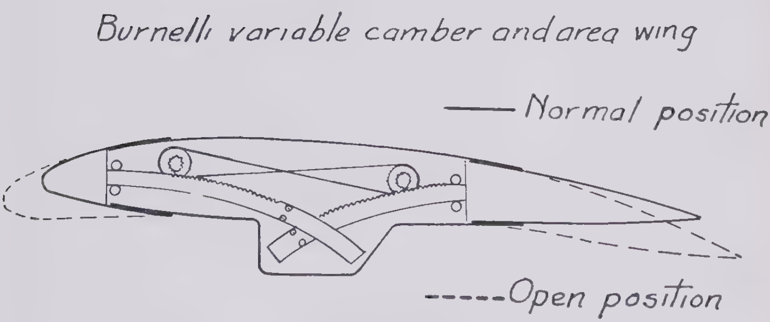
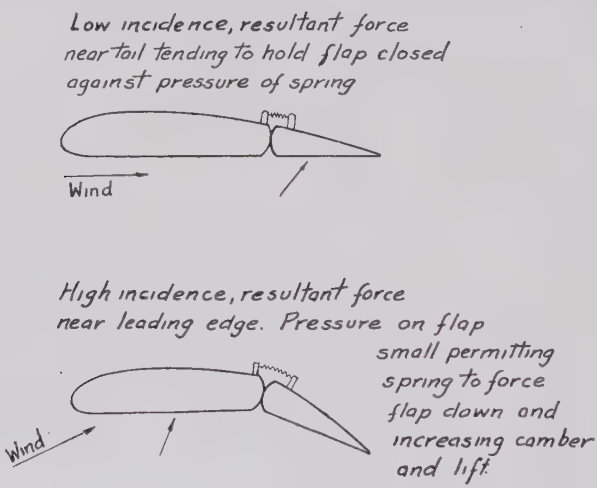


FIGURE 156

fore variable incidence can have no effect on the landing speed. It may have some theoretical advantages in climb and in landing run, but these are too insignificant to be worth the trouble involved.

Flaps

A great many experiments have been tried with hinged flaps, which are exactly like ailerons, but running along the whole length of the wing. When flaps are applied to very thin wings, there can be as much as 50 per cent increase in maximum lift, but the final value of the maximum lift is only about .00375. When the flap is applied to wings of medium thickness it is only possible to obtain some 30 per cent increase, and when applied to high camber wings, the increase is only of the order of some 25 per cent.



Fairey automatic variable camber device.

FIGURE 157

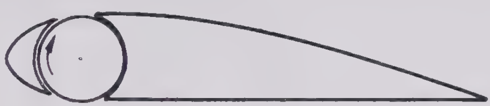
The application of a rear flap is perfectly simple, and is certainly helpful. By the Fairey device shown in Fig 157, the rear flap can be made automatic. The spring always tends to push the flap down, but at low angles of incidence the pressure is concentrated towards the rear of the wing and overcomes the

action of the spring. So at high angles the flap is down and gives us higher lift; at low angles of incidence the wing automatically assumes the contour suitable to high speed.

The use of the rear flap is perfectly sound and helpful; its effects are, however, not sufficiently marked to justify its general adoption.

Rotating Cylinders

In our chapter on airfoil theory we have seen that the lift of a wing depends on the circulation round the wing, which increases the speed above the wing and diminishes the speed below it. It has been frequently proposed that this circulation should be increased artificially by the introduction of a rotat-



Rotating cylinders in wing increasing circulation and lift of wing

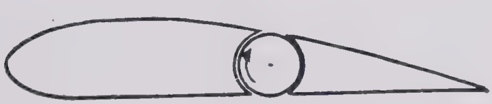


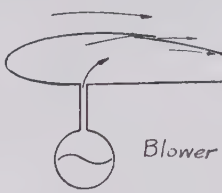
FIGURE 158

ing cylinder within the wing. Different arrangements for increasing the lift in this manner are illustrated in Fig. 158. Very powerful increases in lift can be obtained by such devices. Nevertheless they are not likely to come into general use, because the introduction of such devices breaks up the streamline contour of the wing and thus reduces its efficiency

in normal flight. Again in order to be effective the cylinder would have to rotate in the air at several thousand revolutions per minute. The mechanical difficulties involved in mounting a cylinder in the wing and driving it at such high speeds are obvious. No one would seriously consider the utilization of a rotating cylinder in practice.

Control of the Boundary Layer

Another type of lift increasing device which has not yet passed beyond the laboratory stage is that involving bounday layer control. At the angle of incidence of maximum lift of a



Control of boundary layer by ejection of air on top of wing. Gives high lift at high angle of incidence

FIGURE 159

wing, we know that the flow tears away from the upper surface of the wing and instead of being streamline, appears in the form of whirls or eddies. By applying suction to the interior of the wing as in Fig. 159, it is possible to prevent the break-down of the flow up to angles of incidence as high as 45 degrees, and to secure a lift three times as great as the normal maximum lift. It is also possible to delay the burbling of the wing by ejecting air under pressure from the interior of the wing (Fig. 160). Both these devices are theoretically promising. It remains to be seen what power such methods of control will require for the full size airplane, and what the extra weight and complication are likely to be.

The Handley Page Slot

We now come to the lift increasing device, which in combination with the use of the rear flap is by far the most promising and most practical device yet invented, namely, the Handley Page slot.

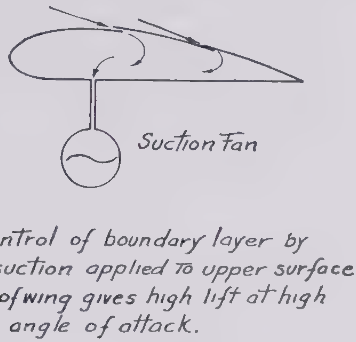


FIGURE 160

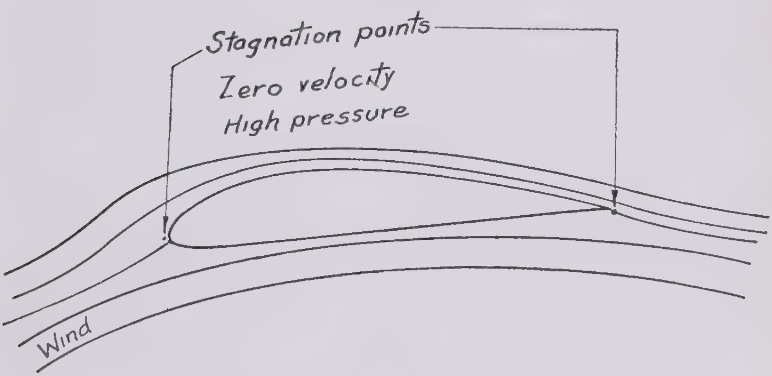


FIGURE 161

To understand the action of the Handley Page slot, it is first of all necessary to examine again the phenomenon of "burbling" at the stall for the ordinary wing. There are two stagnation points for ordinary streamline flow round a wing: one at

the leading edge and one at the trailing edge as shown in Fig. 161. By stagnation points are meant points where the air is at rest relative to the wing, and the pressure is therefore at a maximum. The air on the upper surface of the wing has to flow therefore from one region of maximum pressure to another region of maximum pressure. There is a simple mechanical analogy to this flow of a particle of air from high pressure point to high pressure point, namely that of a ball rolling down a curved surface and then rolling up to the top of a similar curved surface (see Fig. 162). The ball as it rolls down is retarded by the action of friction and unless it has some initial

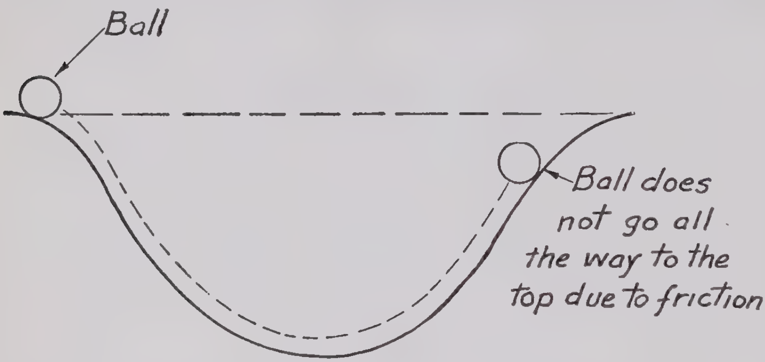
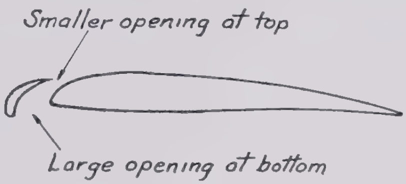


FIGURE 162

velocity is not likely to come up to the top on the second surface. It is more likely to fall back or pull away at some up point on the upward slope. The same applies for the flow of the particle of air. It is likely to tear away from the upper surface of the wing before getting to the second point of high pressure. When the wing is at a high angle of incidence and the lift coefficient is high, the difficulties for the air particle increase so much that it tears away a good distance before the trailing edge is reached and the "burbling," eddying flow follows. The action of the slot, which appears in Fig. 163, is to create a passage from the under side of the wing where the pressure is high to the upper side of the wing which is under

suction. Therefore there is an additional flow of air from the lower surface to the upper surface. If the passage formed by the front auxiliary airfoil and the main wing is properly shaped, with the opening at the bottom somewhat wider than the gap at the top, the air is accelerated in passing through the upper gap. More speed as well as more pressure is thereby added to the air flow on the upper surface of the wing. The air particle gets a species of a "kick" from this auxiliary flow and has therefore no difficulty in getting smoothly to the trailing edge.



Venturi slot in front of leading edge of wing

FIGURE 163

The use of the Handley Page slot therefore retards the "burbling" of the wing. And we have seen in previous chapters that if the lift of a wing occurs at a higher angle of incidence the maximum lift is also increased.

Fixed Slots Ineffective

Experiments have been made with fixed slots of the type shown in Fig. 164. Such slots may be made to increase the maximum lift slightly and also to raise the burbling point to a higher angle. At the same time such fixed slots really constitute a tandem wing. The vortices dropping off from the trailing edge of the front wing put the main wing in a downwash of air and therefore the drag of the system is considerably increased. A fixed slot is likely to be of very little use in reduc-

ing landing speeds and will act very detrimentally on the general efficiency of the airplane.

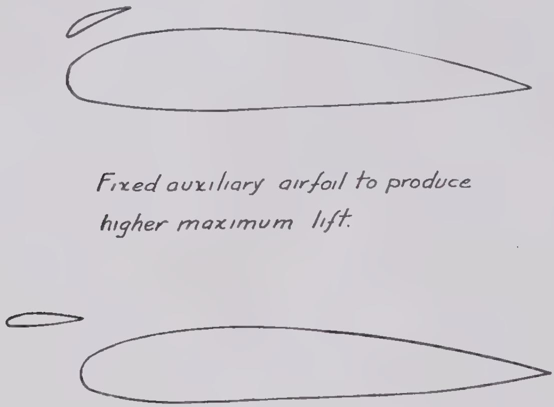


FIGURE 164

Why Slots Should Be Used in Combination with Flaps

About two years ago the author compiled in an article in Aviation the following table of the results obtainable from averaging up a large number of tests.

From this table it is seen that the use of the front slot alone does not give as high an increase in lift as the use of slots in combination with rear flaps. Also the use of the front slot alone means that the maximum lift is obtained at a very high angle of incidence. In order to get the full benefit of the slot, the airplane would have to be built with a high, stilt-like chassis, which is of course a disadvantage from the general design point of view; the landing gear would have to be heavy and would offer also more air drag.

The use of the rear flap with the slot brings the angle of incidence down considerably and therefore makes the use of the slot far more practical.

TABLE No. 1

Type of Section	Average Maximum Camber	Average Increase in Maximum K_y	Burbling Angles of Basic and Slotted Sections	Average Change in Maximum Angle
Effect of front slot alone				
Thick	14.67%	35.8%	15.8° to 24.25°	8.45°
Medium	12.10%	44.0%	12.91° to 20.45°	7.34°
Thin	7.2%	61.0%	14.12° to 25.1°	10.98°
Effect of slots and flaps combined				
Thick	15.1%	43%	16.67° to 22.34°	5.67°
Medium	12.1%	68%	12.91° to 13.75°	.84°
Thin	7.1%	75%	13.17° to 17.83°	4.66°

More Modern Results with Slots

From the above table it would appear that more powerful results can be achieved with thin wings of rather than with thick wings. But more modern experiments both in England and in the United States (including many experiments in the wind tunnel of New York University) have made it quite evident that 100 per cent increase in lift is quite possible even with basic sections of high camber and high lift. In other words it is just as advantageous to apply slots and flaps to thick wings as it is to apply them to thin wings.

So many tests have been carried out on wings of different types with slots of different designs that it is impossible even to summarize these tests in our article.

We will give the results for one wing, the R.A.F. 31, recently published by Mr. Handley Page. These results are illustrated in Fig. 165 and Table 2.

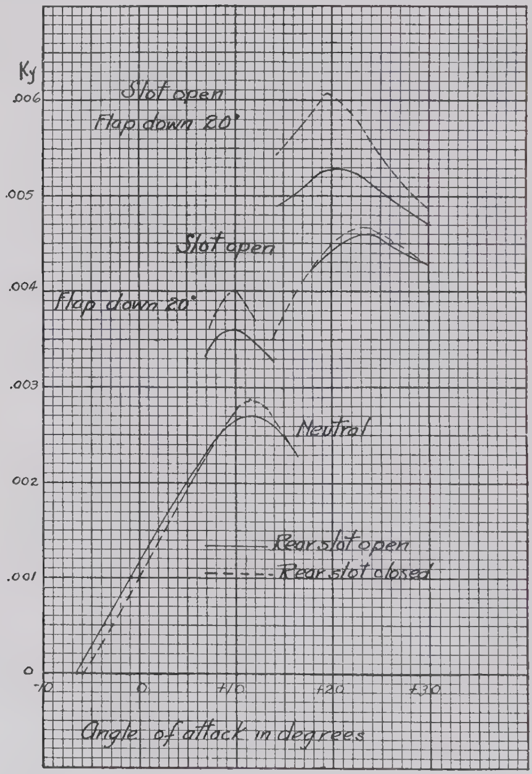


FIGURE 165

From these curves and the table the following results are apparent:

Flaps alone are not very effective.

Slots alone are not very effective, although more powerful in action than the flaps alone.

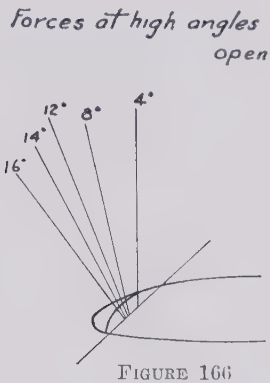


FIGURE 166

TABLE No. 2

Condition	Max. K_y	Angle of Incidence
(1) Front slot closed, rear slot closed, flap neutral	.0028	12°
(2) Front slot closed, rear slot opened, flap neutral	.0031	12°
(3) Front slot closed, rear slot closed, flap down 20°	.00367	10°
(4) Front slot closed, rear slot open, flap down 20°	.00408	10°
(5) Front slot open, rear slot closed, flap neutral	.00470	24°
(6) Front slot open, rear slot open, flap neutral	.00474	24°
(7) Front slot open, rear slot closed, flap down 20°	.00525	20°
(8) Front slot open, rear slot open, flap down 20°	.00602	18°

Slots combined with flaps give extraordinarily high increase in maximum lift, and at the same time the angle of maximum lift remains reasonably low.

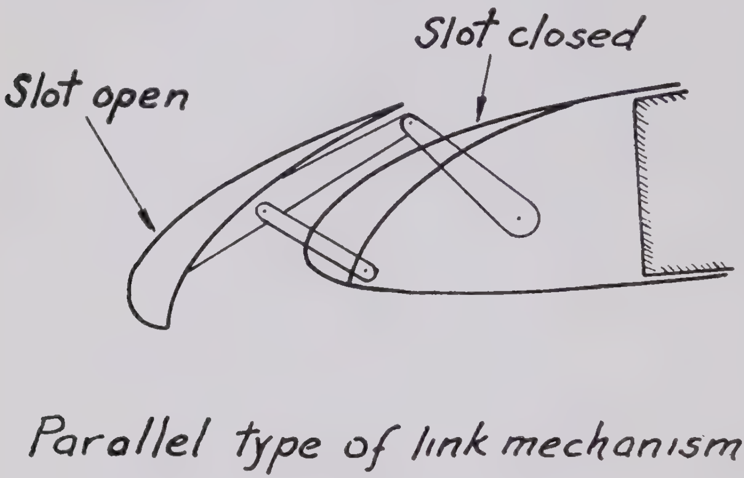


FIGURE 167

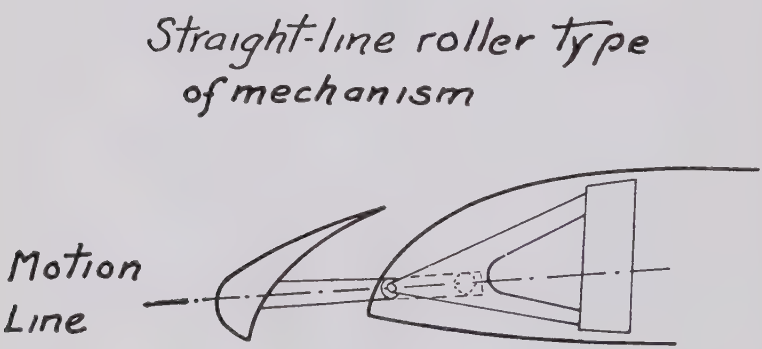


FIGURE 168

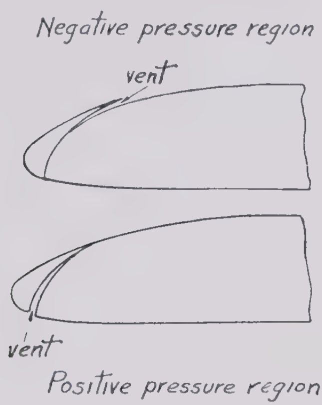
The use of a slotted flap with the front slot is even more effective than the action of an unslotted flap.

Front slot plus rear slotted flap can give a total increase in lift of more than 100 per cent.

The Automatic Slot

The great argument against the use of slots on the part of conservative designers has been that they meant another gadget for the pilot to use.

Wing section with forward aerofoil fitting close on front or on rear edge



To delay opening, slot is vented at top rear edge of auxiliary aerofoil. To hasten opening, slot is vented at bottom front edge of auxiliary aerofoil

FIGURE 169

Within the last two or three years another great discovery by Mr. Handley Page has done much to remove this objection.

And that is the fact that the slot can be made to act automatically.

We have learned in previous articles that as the wing goes

to a higher angle of incidence the suction on the wing goes towards the leading edge (as does the center of pressure) Fig. 166 shows how the resultant force on the front airfoil acts in magnitude and direction as the angle of incidence of the main airfoil changes. With the slot closed and the incidence at 2 degrees the resultant force K_r shown in the diagram acts backwards and there is no tendency for the slot to open. But as the angle of incidence increases, the force on the auxiliary airfoil increases and also moves forward and swings round till it points definitely away from the wing. Now if the slot is

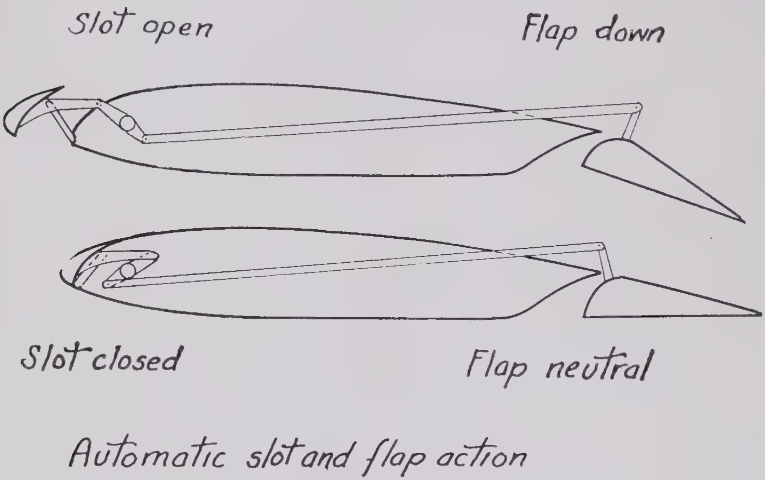


FIGURE 170

mounted on a link motion as in Fig. 167 or on a roller type mechanism as in Fig. 168, then when the main airfoil gets to a large enough angle, the force K_r will evidently open the slot automatically. By suitably venting the slot at the top (see Fig. 169) the opening of the slot may be delayed. By venting the slot at the bottom, the opening may be hastened.

By suitably interconnecting the slot and flap it is possible also to make the action of the flap automatic. When the slot

opens, the flap goes down. When the slot shuts, the flap comes to neutral. The mechanism of Fig. 170 is only one of many that might be devised. It is not so certain that interconnection of the slot and flap is altogether desirable. Under certain conditions the upward force on the flap may overcome the opening tendency of the slot and so close the slot just when its aid is most needed.

Slot Sure to Come into its Own

The results of the Guggenheim Safe Aircraft Competition, won by a Curtiss plane equipped with Handley Page slots and flaps, have shown conclusively that this device is of inestimable value to aviation.

It may be said that with proper design the lift can be doubled, the landing speed reduced by about 20 per cent, the length of run cut down by approximately 75 per cent, and the take off also improved. It is the author's considered opinion that the Handley Page slot is one of the most valuable contributions to practical aerodynamics, and that the next few years will see its use on a great many commercial machines.

CHAPTER XVIII

AERODYNAMICS OF THE BIPLANE

Monoplane versus Biplanes

The evaluation of the respective merits of the biplane and monoplane is not a question solely of aerodynamics. Nevertheless it is of some interest to summarize the arguments for and against the two types.

1. *The Structure of the Biplane Is Apt to Be Lighter.* In the biplane the upper and lower wing are really part of a single truss whose depth is the gap between the two wings. In the cantilever monoplane, that is the monoplane without external bracing, the depth of the truss is only equal to the depth of the spar at any point. And the deeper the truss, the stronger it becomes. Hence the biplane can have smaller wing spars in airplanes of the same gross weight, and generally the structure of the biplane is apt to be lighter. The externally braced monoplane, that is the monoplane with struts running from the fuselage to the wings, has only the outer portion of its wing as pure cantilever. The portion of the wing between the bracing strut and the fuselage has almost the equivalent truss depth of the biplane. Hence the weight of the externally braced monoplane wing lies somewhere between the weight of the biplane wings and the weight of the pure cantilever monoplane (for the same total wing area). Many American designers adopt this compromise structure.

2. *The Biplane Is More Rigid.* Again because of its deep truss the biplane is more rigid, and less liable to twist and flutter. It is only in the monoplane that wing flutter has caused accidents so far.

3. *The Biplane Is Handier.* Because the total supporting area is divided between two wings, the biplane for the same area

will have smaller span and shorter overall length than the monoplane. This makes for more controllability in the air and smaller control surfaces. As our hangars get more crowded, overall dimensions will have a decided bearing on rent of space, and the biplane is likely to be superior in regard to space required.

4. *The Monoplane More Efficient Aerodynamically.* A tapered wing suitable for cantilever construction can be quite as efficient aerodynamically as the thinner wing of a biplane. In the monoplane there are fewer struts and wires to increase the parasite resistance, and what is just as important, less interference between the wing and struts and wires. The maximum lift coefficient of a biplane is less than the maximum lift of a monoplane. The monoplane is apt to be more efficient, aerodynamically, than the biplane, and increase in aerodynamic efficiency offsets its heavier structure.

5. *Nothing to Choose Between Them from a Stability Point of View.* Contrary to opinions sometimes expressed, there is nothing to choose between a biplane and a monoplane from a stability point of view, at least within the normal flying range.

6. *Monoplane Cheaper to Build and Maintain.* Because of its fewer parts, the monoplane is likely to be a trifle cheaper in original construction and maintenance.

7. *Vision Better in a Commercial Monoplane.* The mere fact that in a monoplane there is but one wing to obstruct vision makes the problem of good all round vision simpler in a monoplane. With a cantilever monoplane, though, the large chord at the root offers a difficulty. On the low wing monoplane the wide chord may impede vision on landing.

8. *Nothing to Choose Between Them Regarding Crash Safety.* The one case where a monoplane offers less "crash" safety is in the open cockpit low wing monoplane, where turning over of the plane in landing may be dangerous.

9. *Ease of Making a Parachute Jump.* From the point of view of parachute jumping, the high wing monoplane has somewhat the better of it.

The argument, monoplanes versus biplanes, will continue in-

definitely. Neither type has a really pronounced general superiority over the other, and for specific purposes, sometimes the biplane and sometimes the monoplane will prove the better.

Therefore the aerodynamics of the biplane are well worth studying even at this day.

Definitions for the Biplane

Fig 171 illustrates the definitions of the gap and stagger of a biplane.

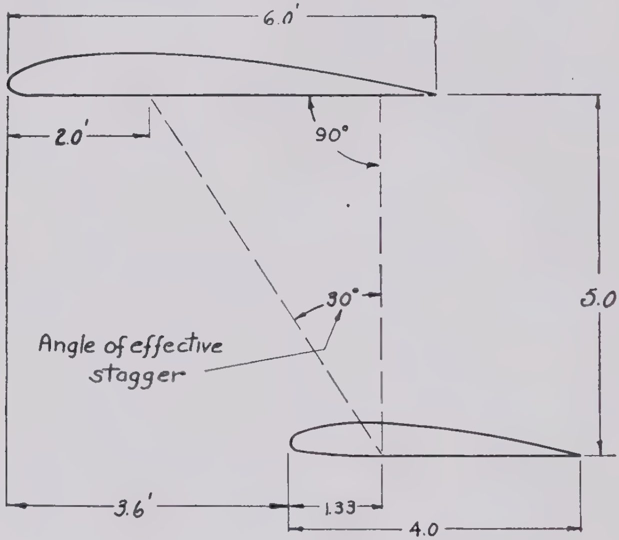


FIGURE 171

The perpendicular distance between the chords is the gap.

The stagger is obtained by joining a point at one-third of the chord from the leading edge of the upper wing to a point at one-third of the chord from the leading edge of the lower wing, and is defined either by

(a) the angle between this line and the perpendicular between the two wing chords,

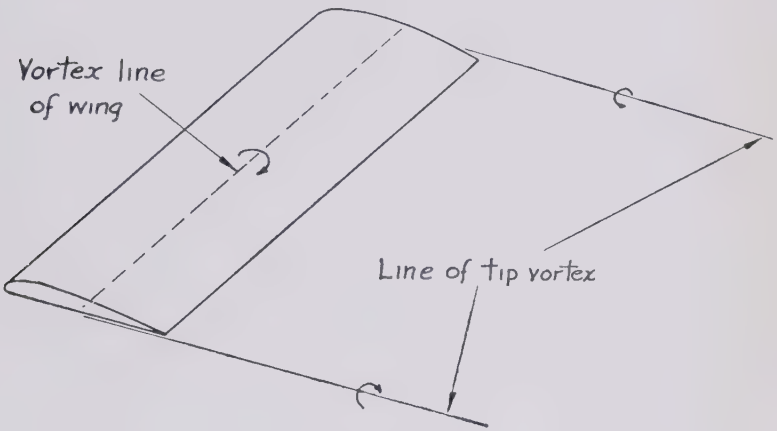
or by

(b) the distance between the leading edges as projected on lower chord.

In technical descriptions of airplanes both values are frequently given.

The gap/chord ratio is the ratio of the gap to the mean

$$\text{chord} = \frac{G}{\dfrac{C_u + C_L}{2}}$$



Vortex system around a monoplane wing

FIGURE 172

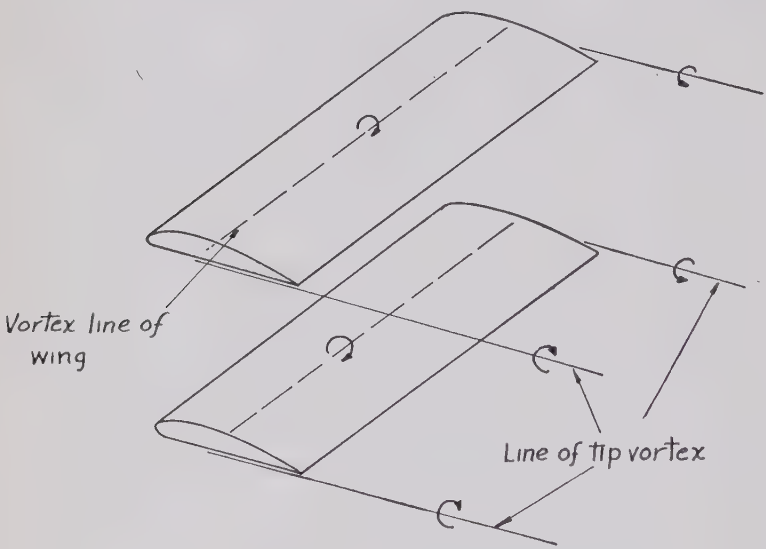
In Fig. 171 the upper chord is 6 feet, the lower chord is 4 feet, the gap is 5 feet and the gap/chord ratio is $\dfrac{6}{(6+4)/2} = \dfrac{6}{5}$.

The stagger in inches is 43.2 and the angle of stagger is 30°.

Elementary Vortex Theory of the Biplane

The complete theory of the biplane is made more complicated than the vortex theory of the monoplane. Even an elementary and approximate knowledge is helpful, however.

In a previous chapter we replaced the monoplane by a vortex line at one-third of the chord, running parallel with the span and by two tip vortices. To refresh the reader's memory, we have redrawn this diagram in Fig. 172.



Vortex system for a biplane

FIGURE 173

A biplane may in similar theoretical fashion be replaced by two lifting vortex lines, and four tip vortices as shown in Fig. 173.

Evidently these vortex lines and tip vortices interact. What is likely to be the effect of this interaction?

Let us first consider the effects of the vortex lines of the wings themselves, which serve to give an image of the circulation round the wing.

The circulation round the upper wing, as can be seen from Fig. 174 decreases the speed of the air past the lower wing.

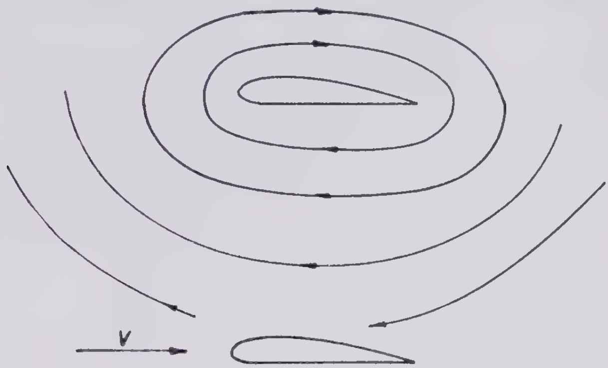


FIGURE 174

The circulation round the lower wing, as can be seen from Fig. 175, increases the speed of the air past the upper wing. Hence one effect of the interaction is to increase the lift of the upper wing and to decrease the lift of the lower wing. That this is indeed a fact is fully confirmed by wind tunnel experimentation.

Now let us consider the effect of the tip vortices.

The tip vortices of the upper wing give the air over the lower wing an additional downwash (Fig. 176). We saw that whenever there is downwash at a wing the lift is swung backwards, and drag is induced thereby. The tip vortices of the upper wing therefore induce an extra drag in the lower wing. Simi-

larly the tip vortices of the lower wing produce a downwash on the upper wing and induce an extra drag for the upper wing.

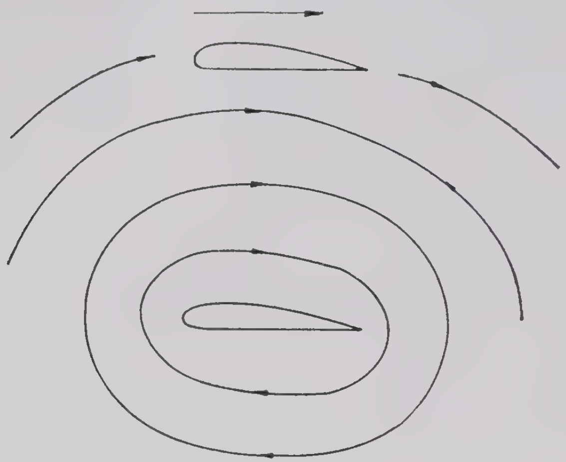


FIGURE 175

Besides the profile drag of each wing we have in a biplane

(a) The self induced drag of the upper wing (that is the induced drag of a similar monoplane wing).

(b) The drag induced in the upper wing by the presence of the lower wing.

(c) The self induced drag of the lower wing (that is the induced drag of a similar monoplane wing).

(d) The drag induced in the lower wing by the presence of the upper wing.

If all these interactions are to be taken into account the theory becomes very complicated.

There are a number of simple results of the theory which we will take for granted:

(1) The induced drag of the biplane improves as the gap/chord ratio increases (naturally, since as the gap/chord ratio increases the interference between the upper and lower wing must be less).

(2) For a given gap, and maximum overall span, that biplane is the most efficient in which the upper and lower wings have the same span and the same chord. (This kills the motion that increased efficiency may be obtained by giving the upper wing more area than the lower wing.)

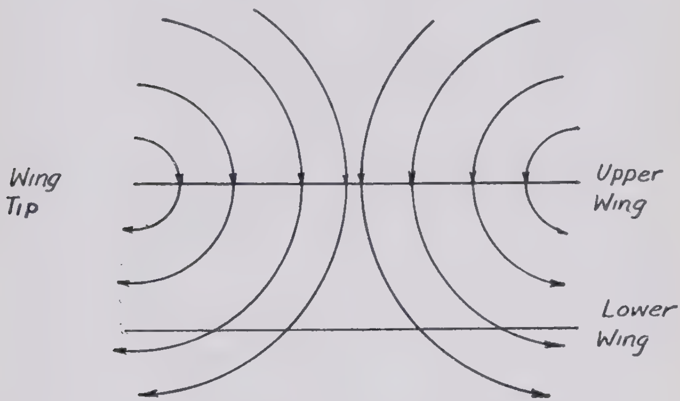


FIGURE 176

(3) As far as induced drag is concerned, a biplane may be replaced by an equivalent monoplane carrying the same load, but having a longer span. (It seems extraordinary, at first sight, that the monoplane should have a larger span, but since it is to carry the same

load as the biplane, its chord will be wider and its aspect ratio will be lower than the aspect ratio of the wings of the biplane.)

Calculating the Efficiency of a Biplane

This equivalent span of the monoplane is obtained by multiplying the span of the biplane by a span factor K, which has been calculated for a great many cases of different gap/chord ratios, different ratios of upper to lower chord, and different ratios of upper to lower span. Since the most efficient biplane for a given overall span has equal upper and lower chords, and since biplanes in practice do not deviate so very much from this rule, it will be sufficient for most practical purposes to know K for this condition only.

For practical calculations, it is better to relate K to the ratio gap/span rather than to gap/chord, and the following table will cover all practical needs.

Gap/Span Ratio	Span Factor for Biplane Wings with Equal Chords and Spans
.05	1.060
.10	1.098
.15	1.130
.20	1.160
.25	1.190

Once the span factor is known it is as easy to calculate the induced drag as it is to make calculations involving aspect ratio.

Example

The maximum lift/drag of the Clark Y wing section, with aspect ratio 6 is 20.6 and the corresponding K_y is .00125. Find the L/D at the same K_y of a biplane of 5 foot chord, 5 foot gap, and 30 foot span, with each wing of aspect ratio 6.

First we must find the total drag coefficient of the Clark Y.

This equals $\frac{K_y}{L/D} = \frac{.00125}{20.6} = .000067$

Then we calculate the induced drag which is given by the formula $\frac{125\ K_y^2}{(A.R.)} = \frac{125 \times (.00125)^2}{6} = .0000325$

The profile drag = total drag — induced drag
= .0000670 — .0000325
= .0000345

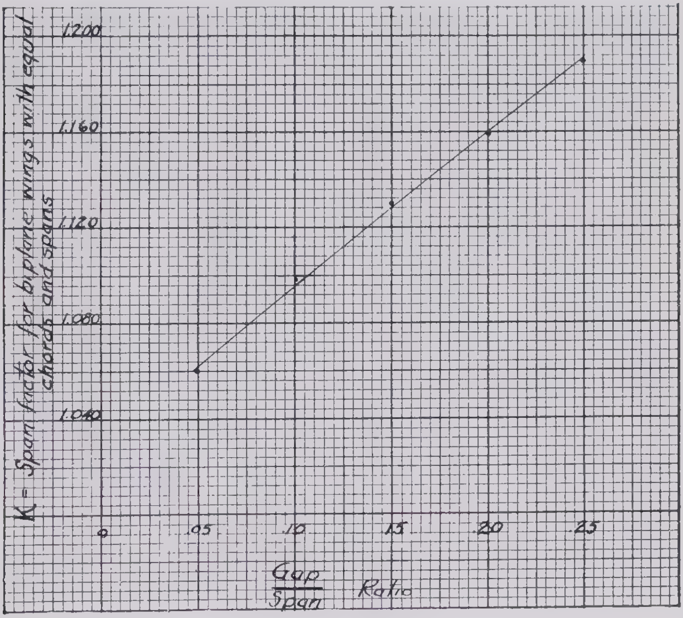


FIGURE 177

Now let us take the biplane. The gap/span ratio is $\frac{5}{30} = 0.1667$.

The span factor is therefore approximately 1.14 (obtained from Fig. 177).

Therefore the biplane is equivalent to a monoplane of chord $2 \times 5 = 10$ feet, and span $30 \times 1.14 = 34.2$ feet. The aspect ratio of the equivalent monoplane is $\frac{34.2}{10} = 3.42$.

The induced drag of the equivalent monoplane, at the same K_y is $\frac{125\ (.00125)^2}{3.42} = .0000574$.

To get the total drag coefficient, we must add the profile drag .0000345 and the total drag coefficient is $.0000574 + .0000345 = .0000919$.

The L/D is $\frac{.00125}{.0000919} = 13.6$.

A biplane with gap/chord of unity therefore loses considerably in efficiency as compared with the monoplane wing having the same aspect ratio as the wings of the biplane.

General Characteristics of an Orthogonal Biplane

A biplane without stagger is termed an orthogonal biplane, and in Fig. 178 are plotted the characteristic curves of a monoplane wing of aspect ratio 6, and of a biplane having wings of the same profile, same individual aspect ratio, and gap/chord ratio of unity.

While the agreement between theory and experiment for a biplane is less close than is the case for the monoplane (because there are certain disturbances introduced by the presence of two wings which theory does not take into account) still the agreement is close enough for practical purposes.

Since the biplane is theoretically replaced by a monoplane wing of lesser aspect ratio than the individual wings of a biplane, its characteristics should resemble the characteristics of a monoplane wing of lesser aspect ratio.

The curves of Fig. 178 indicate that this is indeed the case:

(1) The angle of no lift is not affected by change in aspect ratio, nor is the angle of no lift very different for the monoplane or the biplane.

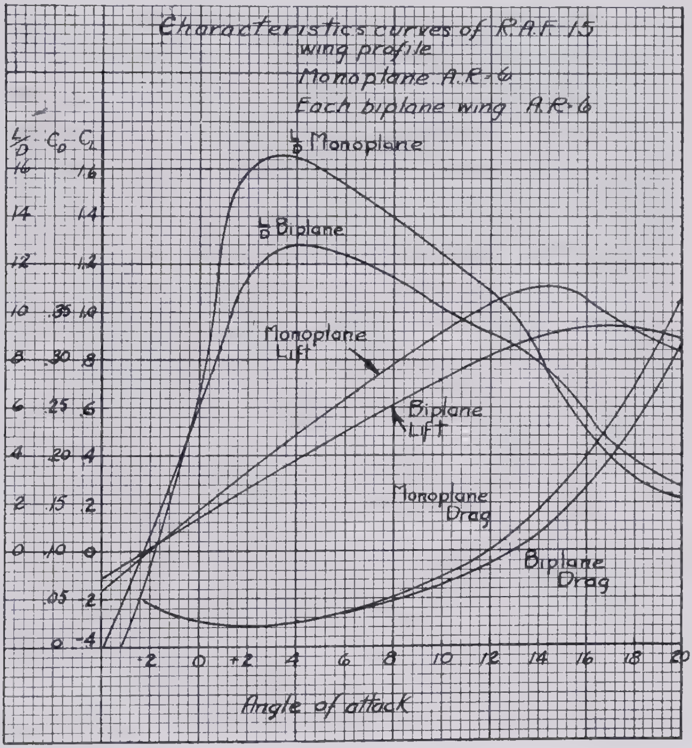


FIGURE 178

(2) At any angle of incidence above the angle of no lift, a wing of less aspect ratio has a greater downwash, and less lift. The biplane shows the same inferiority as compared with the monoplane.

(3) The profile drag is not affected by change in aspect drag, and so the minimum drag is affected very little. Exactly the same holds true for the biplane.

(4) The Lift/drag is always less for the wing of low aspect ratio, as well as for the biplane. The difference in efficiency becomes more pronounced at higher values of the lift coefficient, since the induced drag varies as the square of the lift coefficient.

(5) The maximum lift is less for the wing of lower aspect ratio, and also for the biplane. A reduction of some 5 per cent in maximum lift coefficient is a reasonable practical value.

We are now in a better position to continue the monoplane versus biplane discussion.

At very high speeds the lift coefficient is small, the induced drag of little importance and the profile drag is of paramount importance. Since the biplane, externally braced, can use a thinner section, it is also apt to have the better of the argument on profile drag. To offset the superiority in profile drag there is, however, the resistance of the bracing struts and wires. From the point of view of very high speeds there is probably little to choose between the monoplane and the biplane. In races, such as the Schneider Cup race, monoplanes have sometimes won the day against biplanes and vice-versa.

At cruising speeds, where higher values of K_y are employed, the induced drag is naturally more important. Since the average biplane is equivalent to a monoplane of much lower aspect ratio, the commercial monoplane is apt to be superior to the commercial biplane on the score of fuel efficiency and range.

The most efficient climb, as we have seen previously, is attained at fairly high angles of attack. Hence in climb also the monoplane is apt to be superior.

Rapidity of take-off, landing speed and landing run are largely dependent on maximum lift coefficient. A monoplane, for the same area as a biplane, will have the greater maximum

lift. But the biplane may have a lighter structure. Therefore there is little to choose between the two types on this score.

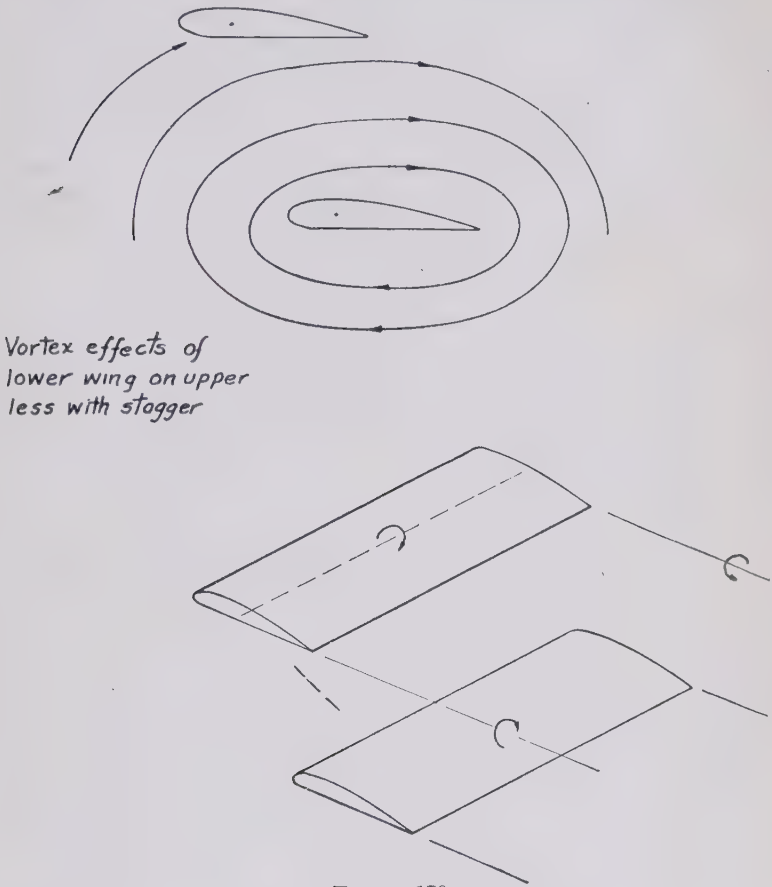


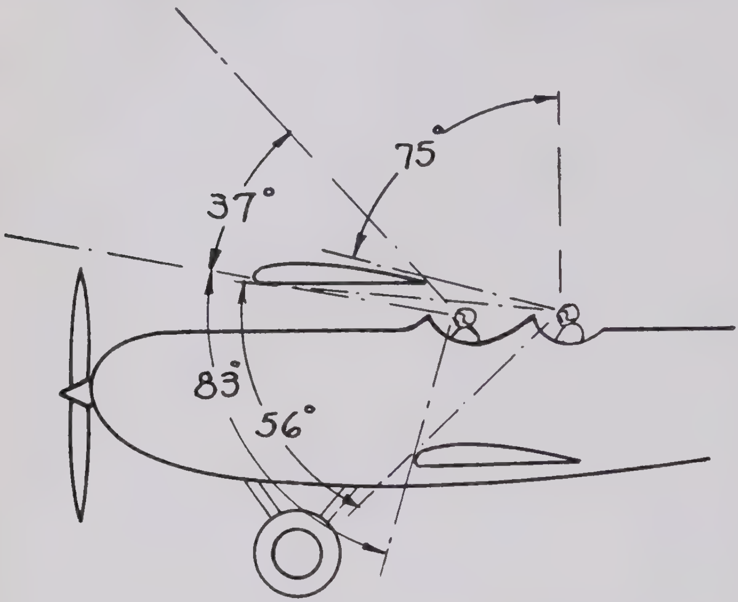
FIGURE 179

Stagger

A full consideration of the aerodynamics of the staggered biplane is beyond the scope of an elementary text. The dia-

gram of Fig. 179 will give us a sufficient idea of what increasing stagger is likely to do.

(1) The upper wing is less influenced by the tip vortices of the lower wing, and experiences less downwash on that account. At the same time, as the upper wing is staggered for-



Positive Stagger for vision ahead and above

FIGURE 180

ward, it not only has the velocity of the air flowing past it increased by the circulation round the lower wing but this circulation also gives an upward component to the air impinging on the upper wing. On the other hand, the circulation round the upper wing will give an advantageous component

to the air impinging on the lower wing. We have seen that in the orthogonal or non-staggered biplane, the lift of the upper wing is greater than the lift of the lower wing (for equal area). Evidently stagger will increase this disparity in lift of the upper and lower wing.

(2) As regards induced drag, the lower wing will be somewhat worse off than in the orthogonal biplane. But the upper wing will not only have its lift increased, but will also suffer less from the tip vortices of the lower wing. On the whole,

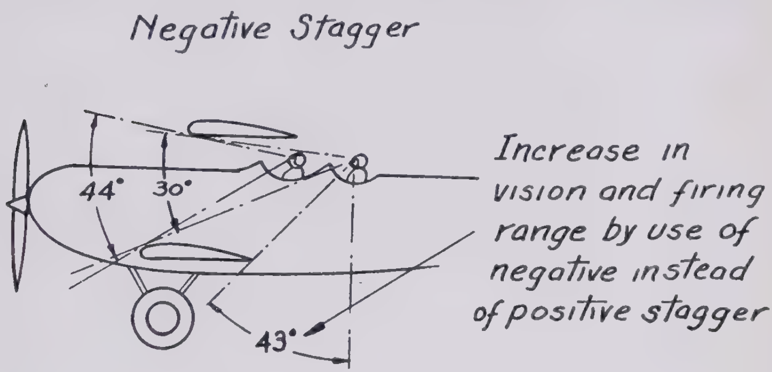


FIGURE 181

therefore, stagger should improve the efficiency or L/D of a biplane combination, and experiment shows that it does.

(3) It is also clear, without further theorizing, that stagger will improve the value of the maximum lift coefficient.

While the aerodynamic effects of stagger are by no means negligible, they are not highly important. In the performance computations required by the Army Air Corps, the effects of stagger are neglected. Besides extreme stagger complicates the structure of the biplane, and introduces very heavy stresses in the rear spar of the wing. A designer is not likely to give his biplane stagger on purely aerodynamic grounds. He is more likely to use stagger because it improves vision or makes a parachute jump easier in a two seater open cockpit

biplane. The possibilities of improving vision by stagger are indicated in Fig. 180.

Negative stagger, as shown in Fig. 181, has been sometimes employed in fighting planes to improve vision and range of fire. Negative stagger, for reasons converse to those of previous argument, tends to give more lift to the lower wing and less lift to the upper. It also tends to decrease the efficiency.

Stagger and Décalage

An interesting biplane combination which is revived once in so often is the staggered biplane with positive décalage, in which the upper wing is set at a larger angle of incidence than the lower wing (Fig. 182). Such a combination gives aero-

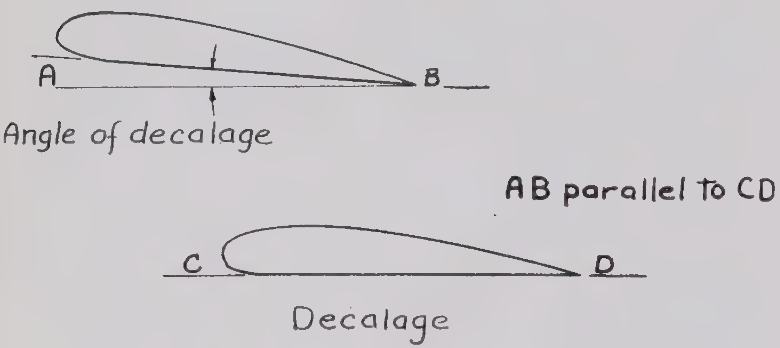


FIGURE 182

dynamic stability. When the lower wing is at a very small angle of incidence its center of pressure moves very far back. But the upper wing working at a larger angle has more lift, and owing to the stagger the point of application of the lift force may be ahead of the center of gravity. Stagger plus décalage, therefore, eliminates the diving moment of the wings at small angles of incidence. Again when at large angles of incidence the center of pressure on the lower wing moves to its foremost position, the upper wing stalls and its lift dimin-

ishes and center of pressure goes back. There is, therefore, no tendency to stall at high angles of attack.

Stagger-décalage, however, introduces uncertainty as to the load distribution between the upper and the lower wing, and also diminishes the efficiency. Comparatively few designers resort to stagger-décalage combinations.

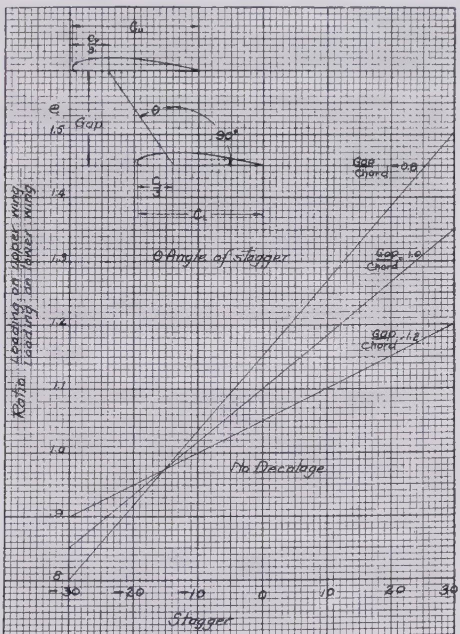


FIGURE 183

Mean Aerodynamic Chord

In considering the longitudinal stability of an airplane, we learned that a forward position of the center of gravity along the chord is helpful, and that the center of gravity should be placed at about 30 per cent of the chord, and we meant thereby the mean aerodynamic chord.

For a rectangular monoplane with constant chord it is quite easy to decide what is the mean aerodynamic chord. It is just the chord of the monoplane.

In a biplane the c.g. must also be placed in reference to the mean aerodynamic chord as illustrated in Fig. 184.

For a tapered monoplane the problem is somewhat harder. If the tapered monoplane can be represented approximately

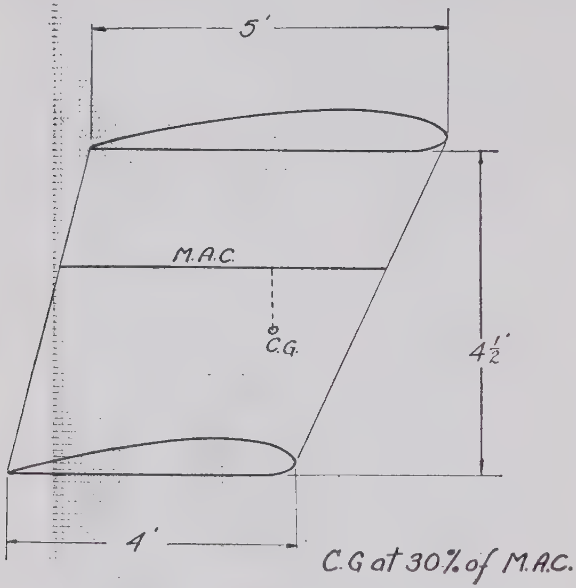


FIGURE 184

by a trapezoid, then a geometrical construction is possible, as indicated in Fig. 185. Let **a** be the chord at the root, **b** at the tip. Lengthen the root chord AB, by the amount b to the point E. Lengthen the tip chord by the amount a, in the opposite direction to point F. Join EF and mid points of a and b. The intersection of these two areas at 0 is the centroid of the two areas and GH is the mean aerodynamic chord, to which the position of the center of gravity may be referred.

To find the Mean Aerodynamic Chord of a biplane is a little more complicated.

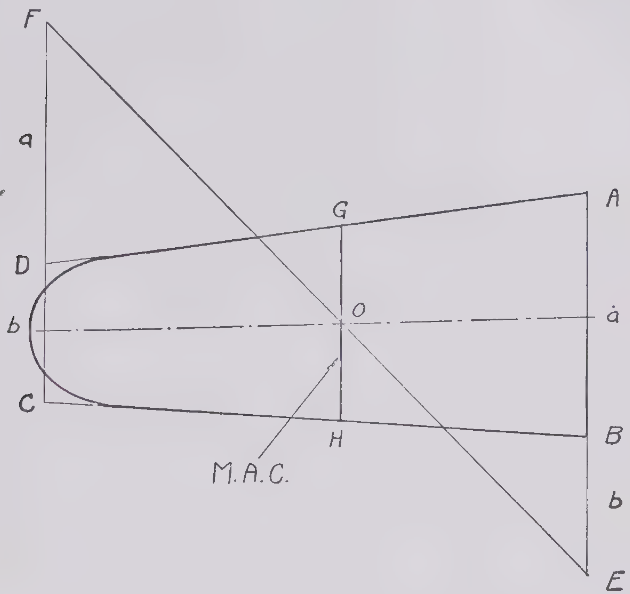


FIGURE 185

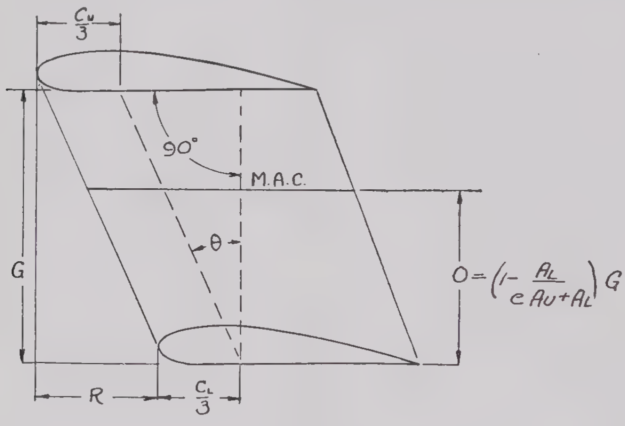
The procedure is indicated in Fig. 186.

The successive steps are as follows:

1. Find the mean aerodynamic chord of the upper wing, C_u.
2. Find the mean aerodynamic chord of the lower wing, C_L.
3. Join the leading edges and trailing edges of these mean aerodynamic chord.
4. Find, e, the ratio of the load per square foot carried by the upper wing to the load per square foot carried by the lower wing.
5. Find the products e A_u C_u (upper wing area by its mean

aerodynamic chord) and A_L C_L (lower wing area by its mean aerodynamic chord).

6. Find the gap G.
7. Divide the gap G in inverse proportions to the values of e A_u C_u and A_L C_L at the point 0.
8. Through the point 0, draw a straight line parallel to the two chords. The length of this line, bounded by the lines between the leading edges and trailing edges of the upper and lower chord respectively is the mean aerodynamic chord of the biplane.



$$\text{Length of M.A.C.} = \frac{e\, C_U A_U + C_L A_L}{e A_U + A_L}$$

FIGURE 186

The finding of the mean aerodynamic chord has an obvious importance in balancing up an airplane.

Example

In Fig. 187 are given the main dimensions of a tapered monoplane, and the position of the center of gravity. At what per cent of the mean aerodynamic chord is the center of gravity?

On the diagram in Figure 187 a line of length equal to the

root chord is laid off above the tip chord (line A B) and a line equal to the tip chord is laid off below the root chord (line C D). A line is then drawn between point B and D. Line E F is then drawn through the midpoints of the root chord and tip chord. The position of the mean aerodynamic chord is then determined by the point of intersection of lines B D and

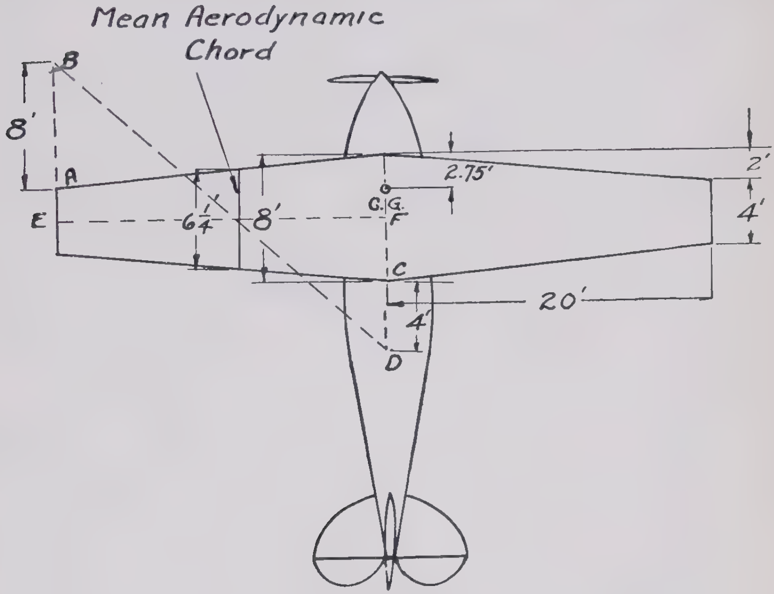


FIGURE 187

E F. The length of this chord is found by measurement to be 6¼ feet. The difference between the root chord and the tip chord = 8 — 6.25 = 1.75 feet. One-half of this difference gives us the distance between the leading edge of the root section and the leading edge of the mean aerodynamic chord. Therefore the c.g. is $(2.75 - \frac{1.75}{2})$ feet behind the leading edge of

the mean chord or 1.875 feet. Therefore in per cent of the mean chord from the leading edge the c.g. is $\frac{1.875}{6.25}$ or 30% of the mean chord from the leading edge.

Example

In Fig. 188 are given the main dimensions of a staggered biplane, with rectangular wings of unequal chords and span, and the position of the center of gravity. Find at what per cent of the mean aerodynamic chord the designer has placed the center of gravity.

Gap chord ratio:

$$\text{Average chord} = \frac{5 + 4}{2} = \frac{9}{2} = 4.5 \text{ feet}$$

Gap = 5 feet.

$$\frac{\text{Gap}}{\text{chord}} = \frac{5}{4.5} = 1.11$$

Effective angle of stagger

$$\theta = \tan^{-1}\left(\frac{\frac{4}{3} + 2.5 + \frac{5}{3}}{5}\right) =$$

$$= \tan -1 \left(\frac{2.17}{5}\right) = 23.5°.$$

Then from chart of Figure 183

e = 1.23

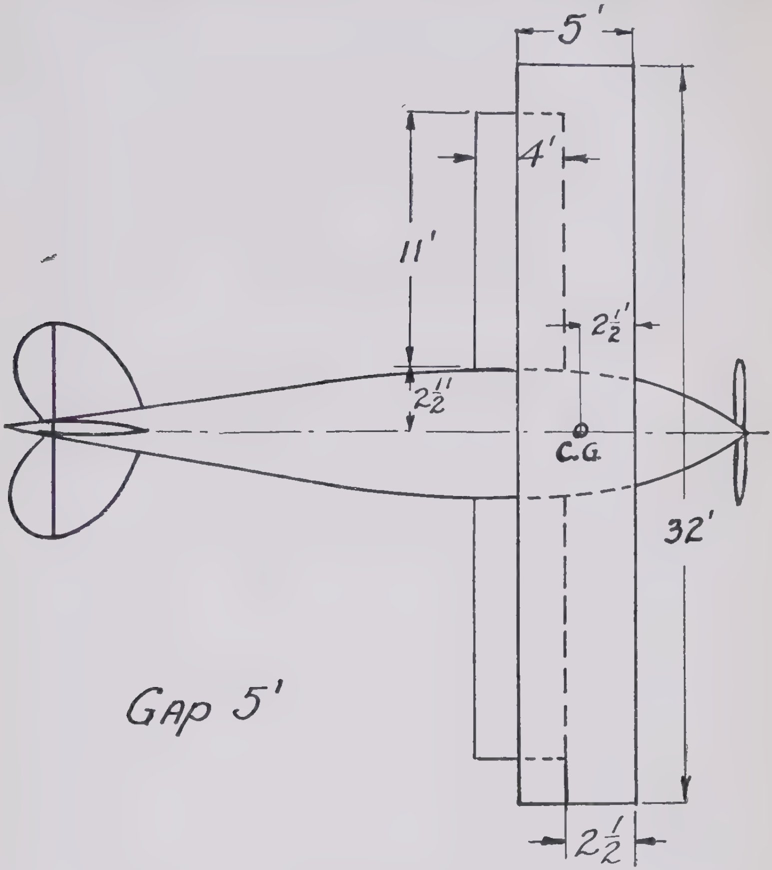


FIGURE 188

Length of mean aerodynamic chord

$$\text{M.A.C} = \frac{e\, C_u\, A_u + C_L\, A_L}{e\, A_u + A_L}$$

$$= \frac{1.23 \times 5 \times 160 + 4 \times 88}{1.23 \times 160 + 88}$$

$$= 4.69 \text{ feet}$$

Distance between lower chord and M.A.C.

$$= (1 - \frac{A_L}{eA_u + A_L})\ G$$

$$= (1 - \frac{88}{196.5 + 88})\ 5$$

$$= .691 \times 5 = 3.45 \text{ feet.}$$

Leading Edge (L.E.) of M.A.C, is behind upper L.E. by

$$\left(\frac{2.5}{5}\right)\left(5 - 3.45\right) = 0.775 \text{ ft.}$$

therefore c.g. is placed by the designer,

$$\left(\frac{2.5 - 0.775}{469}\right) 100 = 36.9\% \text{ of M.A.C.}$$

Load Distribution Between Wings

The upper wing of a biplane carries a greater proportion of the load as the stagger increases, and the effect is intensified as the gap/chord ratio is diminished. Of course, the distribution of the loads between the two wings varies with the angle of attack. The graphs of Fig. 183 are not strictly accurate therefore, but they give a fair average and are in wide use by designers.

Example

In Fig. 184, are shown the dimensions of a staggered biplane, with equal spans of 40 feet, but a top chord of 5 feet, and a bottom chord of 4 feet, and a gap of 4½ feet, that is a gap/chord ratio of 1. The angle of stagger is 20 degrees. If the gross weight of the airplane is 3,600 pounds what load is carried by the upper wing.

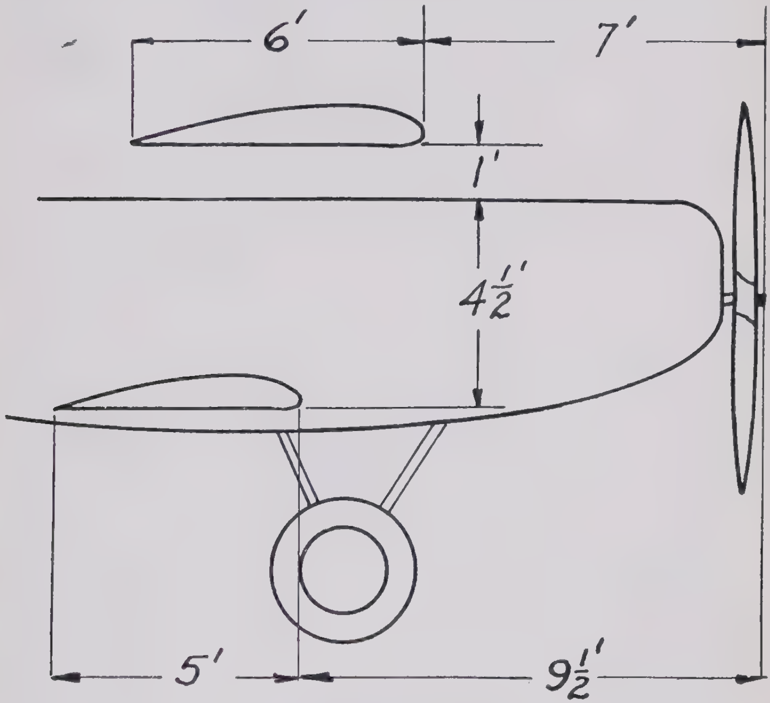


FIGURE 189

Consulting the charts of Fig. 183, we find that for a gap/chord ratio of 1, and a stagger of 20 degrees, the load per unit area carried by the upper wing is 1.27 times that of the lower wing.

Let w be the load per square foot carried by the lower wing. Then 1.27 w is the load per square foot carried by the upper wing, and

$$w\ (4 \times 40) + 1.27\ w\ (5 \times 40) = 3600 \text{ and } w = 8.75.$$

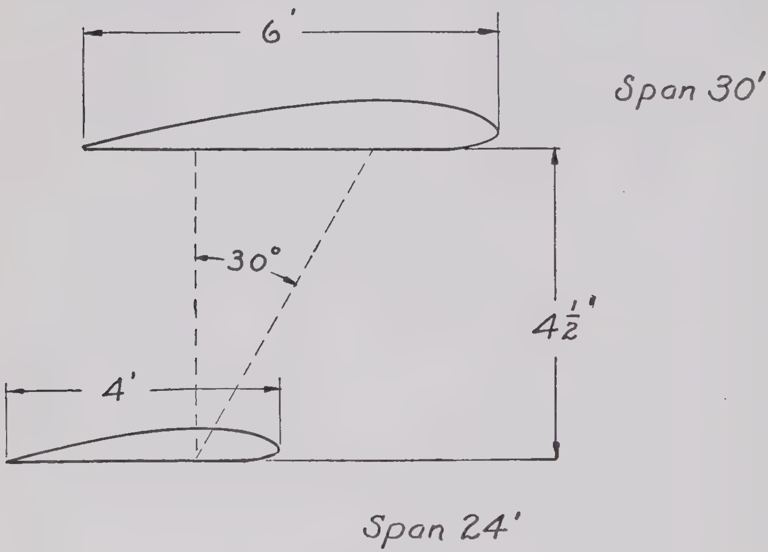


FIGURE 190

Therefore the upper wing carries $1.27\ w\ (5 \times 40) = 2230$ pounds.

Problems

1. In Fig. 189 are shown the side dimensions of a biplane. Find the stagger in inches, and in angle of stagger. Find the gap/chord ratio.

   Ans.: 30 inches
   21.4 degrees
   Gap/chord = 1

2. The upper and lower wings of an orthogonal biplane are rectangular and have a chord of 6 feet, and a span of 36 feet. The gap is 5 feet. Find the span and aspect ratio of the equivalent monoplane.

   Ans.: 41.5 feet
   3.46

3. If the profile drag of the wings in this biplane is .000035, what is the L/D of each wing individually when its Ky is .0015. What is the overall L/D of the biplane at this Ky.

   Ans.: Monoplane L/D = 18.34
   Biplane L/D = 12.84

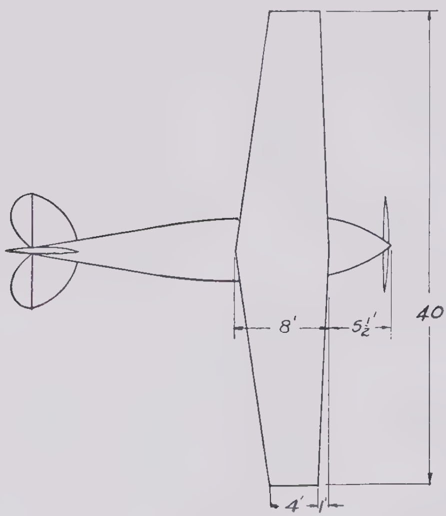


FIGURE 191

4. A biplane has stagger of 30°, upper chord 6 feet, lower chord 4 feet, gap 4½ feet (Fig. 190). What is the ratio of load per square foot carried by the upper wing, to the load per square foot carried by the lower wing. If the span of the upper wing is 30 feet, the span of the lower wing

is 24 feet, and the airplane is loaded to a mean value of 8 pounds per square foot, what is the proportion of the total weight carried by the upper wing.

Ans.: Upper carries 726 of total weight.

5. Find the mean aerodynamic chord of the tapered wing monoplane of Fig. 191 and indicate a desirable position for the center of gravity measured along the mean aerodynamic chord.

Ans: M.A.C. 6.02 feet.

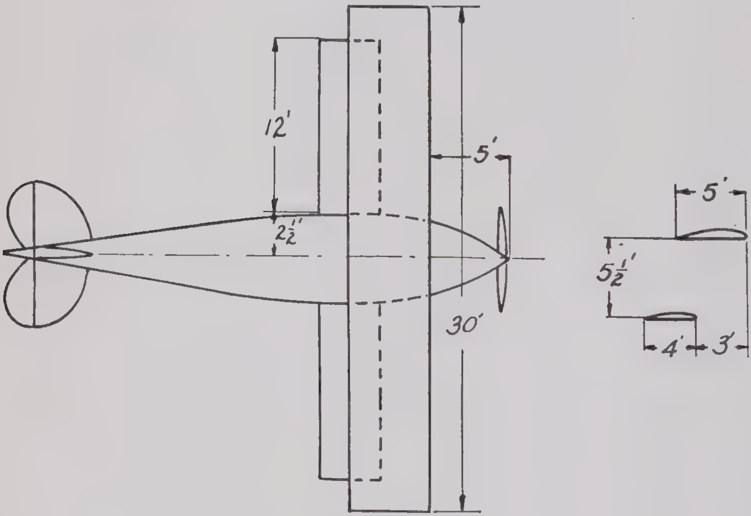


FIGURE 192

6. Find the mean aerodynamic chord of the biplane shown in Fig. 192 and indicate a desirable position for the center of gravity measured along the mean aerodynamic chord.

Ans: M.A.C. = 4.65 feet.

CHAPTER XIX

RESISTANCE OF PARTS AND AERODYNAMICS OF A COMPLETE AIRPLANE

The calculation of the parasite resistance of an airplane is a difficult matter because:

1. The resistance coefficient of any part varies with the product of its size and speed; there is a "scale effect" in aerodynamic language.

2. There is interference between parts. The air resistance of two objects placed close together may actually be greater than the sum of their individual resistances.

3. The model of a particular fuselage, nacelle or similar part may never have been tested in the wind tunnel, and it is then necessary to pick out at least a somewhat similar body as a basis for calculation.

4. The slip stream of the propeller affects the resistance of objects within its area, and the presence of objects in the slip stream affects the thrust and efficiency of the propeller.

An accurate estimate of the parasite resistance of an airplane therefore requires much investigation and experience, and many designers prefer to make their calculations directly from a wind tunnel test without making detailed estimates of parasite resistance. The following notes should be considered as elementary and as purely an introduction to the subject.

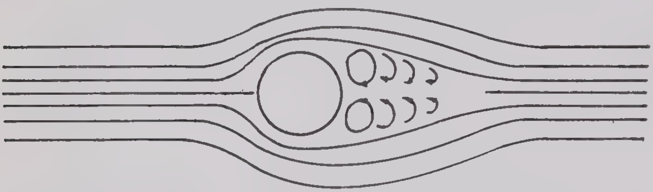
Resistance of Cylinders

Exposed round tubes are occasionally used in airplane construction, although they have considerably more resistance than streamline sections of the same projected areas, because they may be too short to make streamlining worth while, or be located in such a position as to make streamlining difficult.

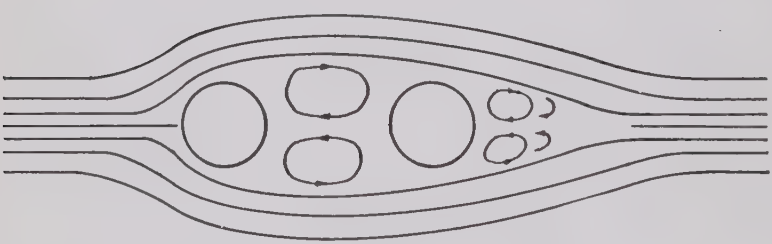
The following is a fairly reliable formula for the resistance of a cylinder:

$$R = .000265\ D\ L\ V^2$$

where R = resistance in pounds per foot of length.
D = diameter of cylinder in inches.
L = length of cylinder in feet.
V = speed in miles per hour.



One cylinder produces large eddies and large drag



Two cylinders in tandem give less eddies then two single cylinders as resultant flow is more streamline

FIGURE 193

Example

What is the resistance of a 6 foot cylinder, 2 inches in diameter, at 100 miles per hour?

$$R = .000265\ (2)\ (6)\ 100^2$$
$$= 31.8 \text{ pounds}$$

This calculation shows what enormous resistances may be the penalty for exposing round tubing.

Round wire may be calculated on the basis of the coefficient given for the cylinder.

Values for stranded cable, which naturally offers greater resistance than plain round wire, may be obtained by adding 20 per cent to the resistance of round wire of similar size.

When wires are inclined to the wind, it is sufficiently accurate to base calculations on the length projected normally to the wind.

To allow for exposed turn buckle and fittings an empirical rule given by the Army Air Corps, is to add 2 feet of length per wire or cable.

Two types of fairings for
two wires in tandem

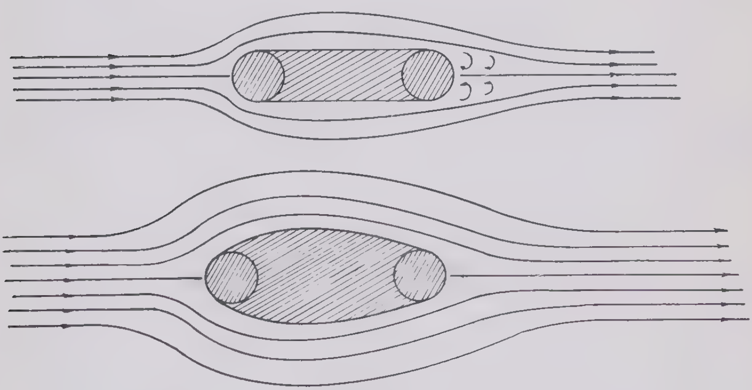


FIGURE 194

Wires or Cables in Tandem

When two wires or cables are placed in tandem, the combination tends to produce a certain streamline effect as indicated by the diagram of Figure 193. In such cases the coefficient of a single wire multiplied by 1.5 is used.

If two wires or cables in tandem are connected by fairing as indicated in Figure 194, the streamline effect is even better, and the coefficient of a single wire can be used.

Streamline Wire

Of recent years the streamline wire, of the cross-section shown in Figure 195, has been successfully produced and widely used on airplanes. This wire has considerable aero-

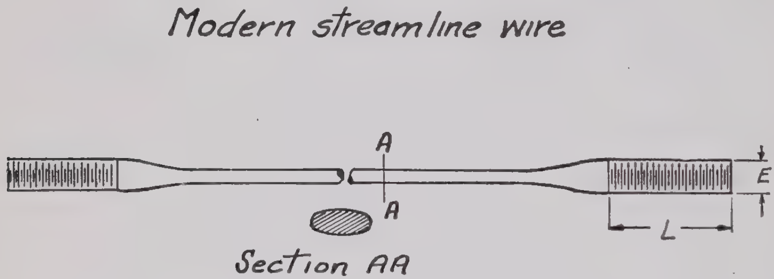


FIGURE 195

dynamic advantage over round wire or cable. The resistance coefficient, K, in the formula:

$$R = K\,D\,L\,V^2$$

where R = resistance in pounds.
D = thickness of wire in inches.
L = length in feet.
V = speed in miles per hour.

is about one-third of that of a round wire, and is estimated as being between .000085 and .000097, with .00009 a fair average value for practical calculations.

The actual advantage of using a streamline wire is greater than would appear from a consideration of drag for a given projected area, because the streamline wire has a greater cross-sectional area and a greater strength for a value of D equal to the diameter of a round wire.

Example

The following calculation will make this clear:

1. A single lift wire 6 feet in length is required to carry an ultimate load of 2,100 pounds. At a speed of 100 miles per hour, what will be the resistance of a round swaged wire, and of a streamline wire used for this purpose?

In Figure 196 are shown the dimensions of the two types of

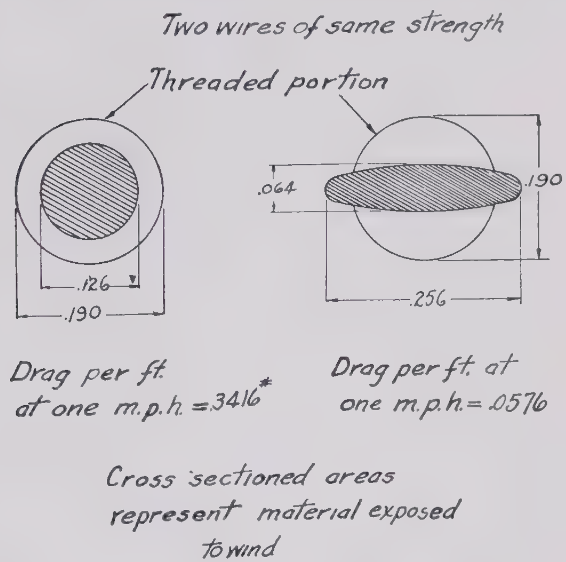


FIGURE 196

wires giving approximately the same ultimate strength. The round wire has, then, a diameter of .126 inches, and the streamline wire a maximum thickness of .064 inches.

The resistance of the round wire $= .000265\ (.126)\ (6)\ 100^2$
$= 2.05$ pounds

The resistance of the streamline wire $= .00009\ (.064)\ (6)\ 100^2$
$= .345$ pounds

or approximately one-sixth of that of the round wire.

In view of this marked advantage of the streamline wire, it may be asked why it is not always employed in preference to stranded cable (over which its aerodynamic advantage will be still more marked).

One reason is that double life wires placed in tandem are current practice. Wires or cables placed in tandem, particularly with a fairing in between, have their resistance appreciably decreased (as we have stated previously). Streamline wires placed in tandem show little or no improvement because they are already streamlined in themselves, and the tandem arrangement scarcely adds to the streamline effect.

Another and much more important reason is that solid streamline wire, no matter how carefully made, may, under vibration, snap without warning. A stranded cable will show fatigue, with one or two strands fraying or breaking first and giving warning to the careful mechanic or inspector.

Since the streamline wire is "cleaner" than a round wire, the relative resistance of its end fittings will be greater. The Army Air Corps recommends therefore that for streamline wire 3 feet be added to its length to allow for terminals and fittings.

Resistance of Struts

The aerodynamic comparison of two struts of different form is somewhat more difficult than that of two wires.

With wires, the strength in tension is more or less independent of the form, and dependent solely on the cross-sectional area, and the characteristics and manufacture of the steel. The weight of the wire for a given load is therefore also independent of its form.

The strength of a strut, carrying a compressive load, depends greatly on its form.

A strut in compression will fail about that axis which has the least moment of inertia. The moment of inertia about any axis is dependent on the distribution of the material relative to that axis, and the distance from that axis of the bulk of the material. This point is illustrated by the sketches of Figure 197.

The round tube will have the same strength, when acting as a strut, about any axis, from considerations of symmetry.

A streamline strut, whether solid or hollow, will have a greater strength about the transverse axis B B, than about the longitudinal axis A A, because the material is so distributed

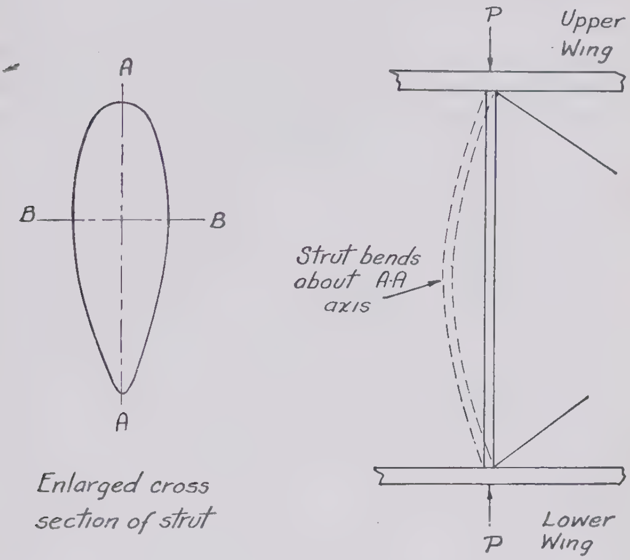


FIGURE 197

as to be further from the axis B B. Hence for the same load a streamline strut will weigh more than a round strut. As the "fineness" of the strut, that is the ratio of the length to thickness increases, the discrepancy in weight for a given load will increase also. As extra weight is equivalent to extra aerodynamic resistance, part of the advantage of the streamline strut disappears.

The calculation of the best shape of strut for a given plane and position on that plane is a matter of some complication,

and in practical design the following empirical rule is probably close enough.

(a) Planes under 100 miles per hour, fineness ratio of between 2.5 and 3.0.

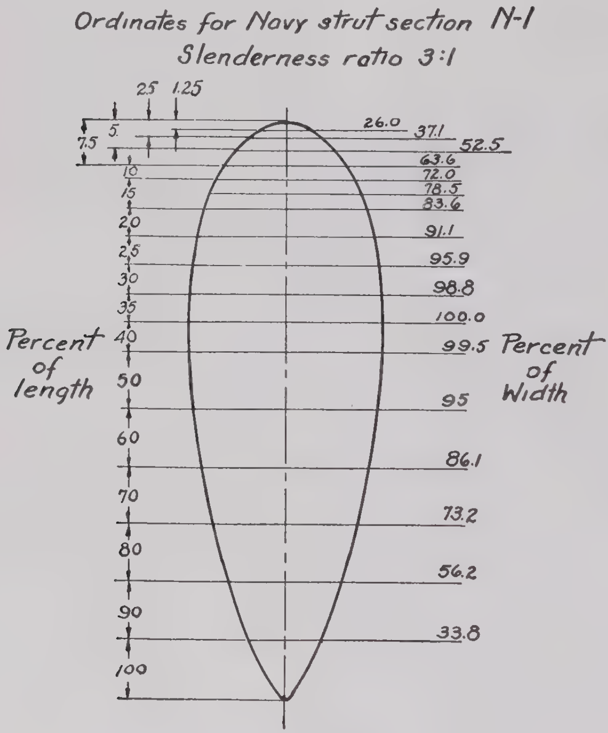


FIGURE 198

(b) Planes between 100 and 150 miles per hour, fineness ratio of 3.

(c) Planes over 150 miles per hour, fineness ratio of between 3 and 3.5.

This rule is based on the consideration that parasite drag

becomes more and more important and the weight less important as the speed increases.

One of the best struts ever developed is Navy No. 1 Strut, which is shown in Figure 198, with offsets in per cent of the maximum thickness D marked along its length. The strut shown in Figure 198 has a fineness ratio, L/D of 3.

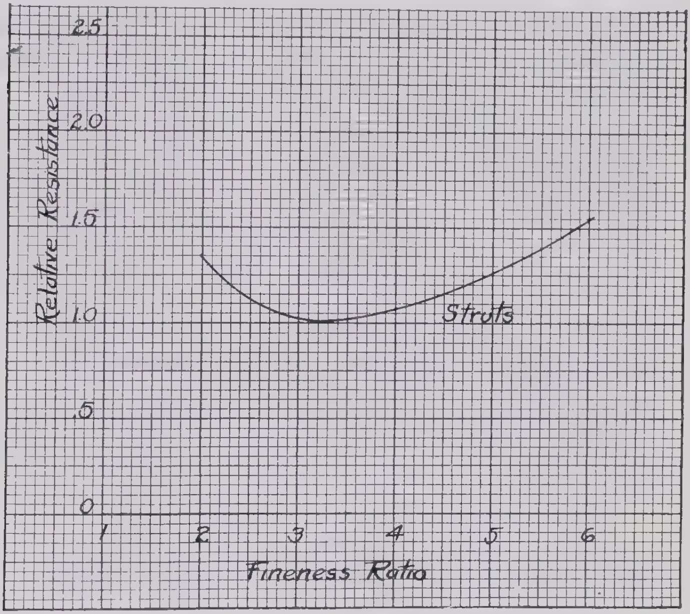


FIGURE 199

For a full size strut of fineness ratio 3 the Army Air Corps recommends an average coefficient of .0000183 in the formula.

$R = K\,D\,L\,V^2$

with these symbols having their usual significance. Corrections for fineness ratio may be taken from the diagram of Figure 199, from which it is apparent that the resistance increases when the strut gets so short as to approach a round cylinder, and

increases also for an inordinate fineness because the increase in skin friction begins to counteract the decrease in head resistance, with a fineness ratio of 3 apparently giving the least drag coefficient.

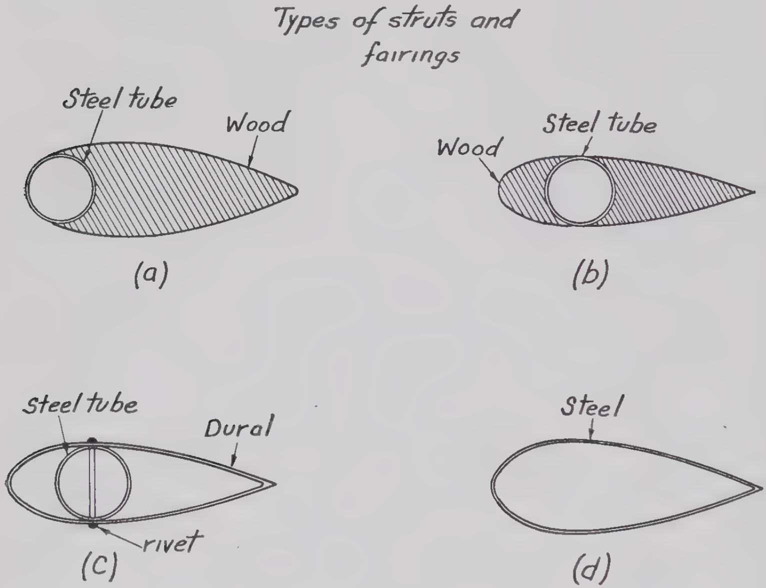


FIGURE 200

Formerly interplane struts were almost invariably made of solid wood, but modern practice calls almost exclusively for the types shown in Figure 200 (a) round steel tube with spruce or balsa fairing at rear only (b) round steel tube with spruce or balsa fairing, both front and rear (c) round steel tube with continuous fairing of sheet aluminum (d) streamline steel tubing.

When computing the resistance of a round steel tube with fairing, it is best to increase the resistance values of the ideal strut by some 20 per cent, to allow for imperfections of the streamline form.

For slow planes, wooden struts have just as good an overall aerodynamic efficiency as steel tube struts, but for fast planes, the steel streamline tubing is probably most desirable. No general rules can be given. The careful designer will investigate each case on its own merits, taking aerodynamic resistance, weight, cost, and ease of maintenance into consideration.

Only one positive assertion can be made. External struts made of duralumin tubing should never be used.

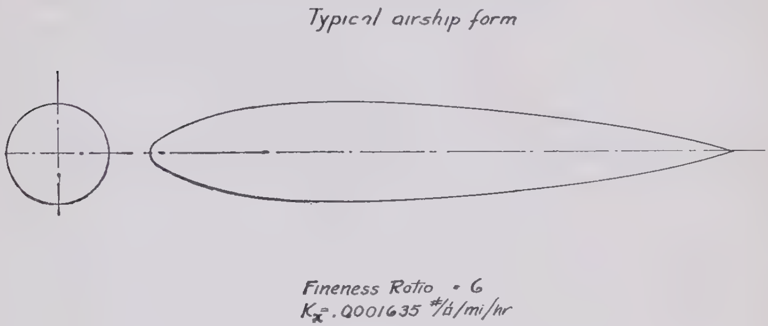


FIGURE 201

The strength of a long-pin jointed strut is given by the formula $P = \dfrac{\pi^2 E I}{L^2}$

where P is the buckling load

E = Modulus of elasticity of the material.

I = Least moment of inertia.

L = Length between pin joints.

The modulus of elasticity of steel is 30,000,000, that of duralumin is only 10,000,000. By an argument, somewhat too advanced for this text it can be shown that this difference in moduli will make the overall efficiency of an exposed dural strut much less than that of a steel strut, even allowing for the lighter specific weight of the dural.

Fuselage Resistance

The drag coefficient of a good airship form such as that shown in Figure 201 is only .0001635 pounds per square foot of the maximum cross-sectional area per mile per hour or only 5.1% of the drag coefficient of a flat plate.

In Figure 202 an almost perfect streamline fuselage shape whose drag coefficient is only .00016, or just about 1/20th of

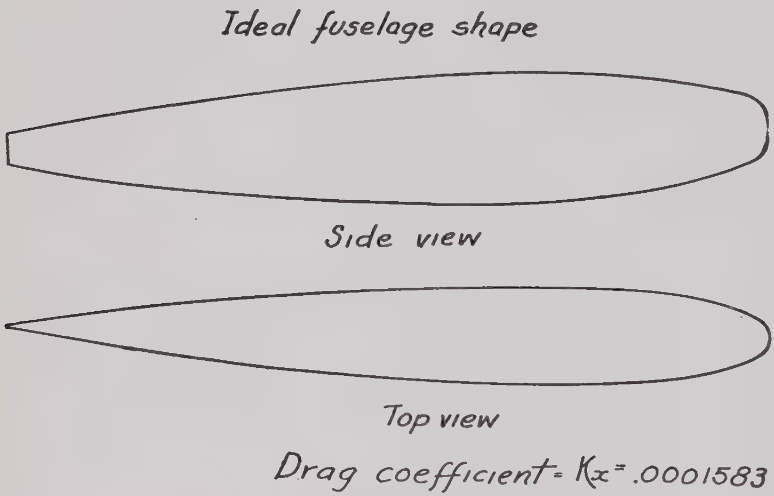


FIGURE 202

that of a square plate. (See Diehl's Engineering Aerodynamics.)

These remarkably low values of the drag coefficient cannot even be approached in practice, because the fuselage is broken up by cockpit openings, windshields, engine cylinders, exhaust rings or stacks, etc.

An illustration of what apparently minor disturbances can do to increase the fuselage resistance is given in Figure 203. With the introduction of the pilot and windshield, the resistance of the fuselage was almost doubled.

The forms of fuselages are so varied that it is impossible to set forth specific rules to cover all types.

In Figure 204 are given sketches of two typical fuselages, together with the drag coefficients based on the maximum cross-sectional area.

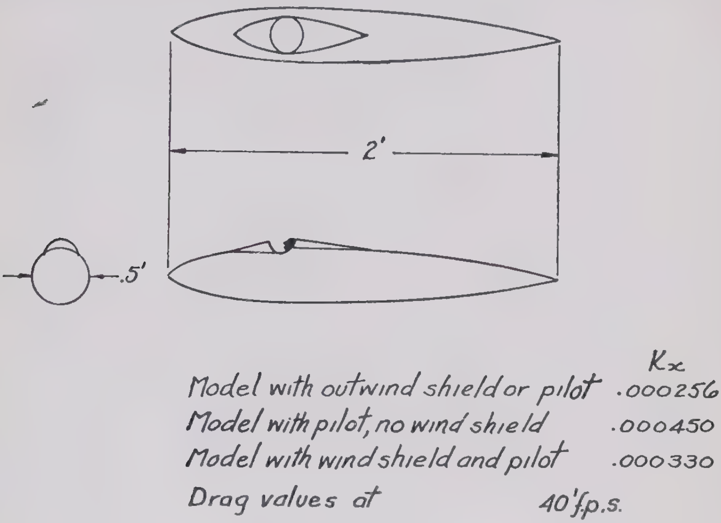


FIGURE 203

From this diagram, the following important points emerge:

(1) The resistance coefficient of an enclosed cabin fuselage is less than that of an open cockpit machine.

(2) Rounding off the corners of a fuselage is helpful.

(3) The resistance of a fuselage is greatly increased by the projecting cylinders of an air-cooled engine.

(4) The Venturi cowling improves the resistance very considerably.

Cowling in of the Engine

Much attention has been given of late to special cowling in of the engine. Both wind tunnel and flight tests indicate that

much saving in resistance and improvement in performance is possible. With care, the cooling of the engine need not be impaired. As an alternative to the N. A. C. A. or Venturi Cowl-

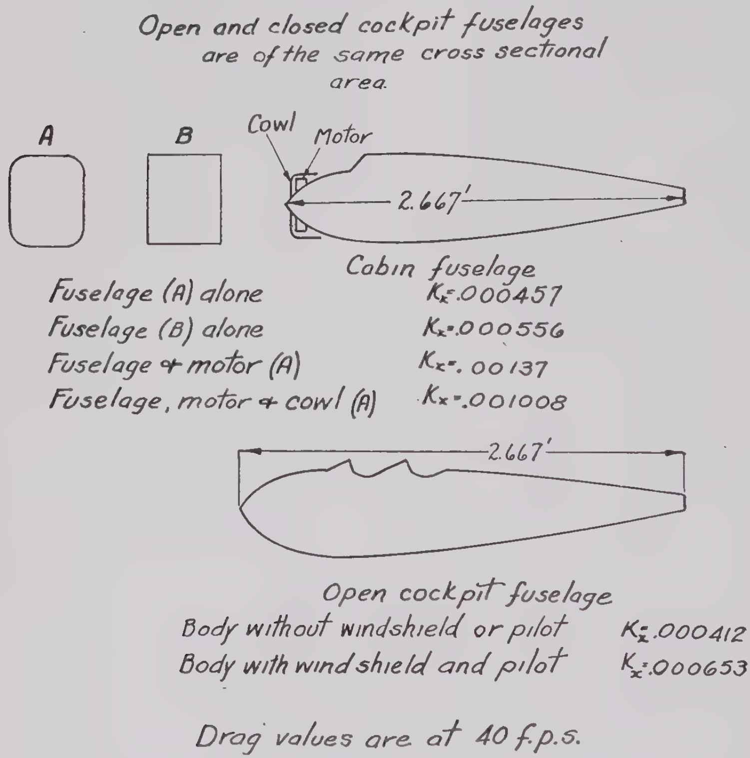
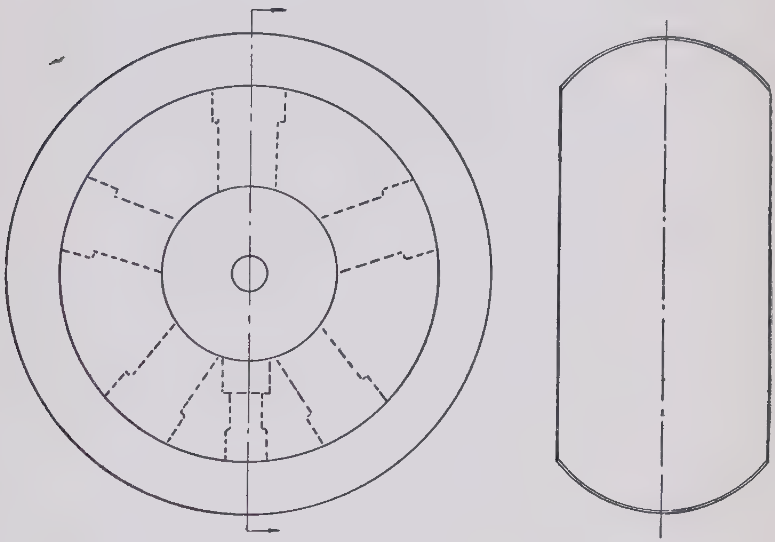


FIGURE 204

ing, the Townend ring (see Figure 205) is sometimes employed. While not quite so effective in reducing drag as the Venturi Cowling, it is nevertheless very helpful, is much simpler to make and hinders the pilot's vision less.

The following is an elementary and qualitative theory of the Venturi Cowling, as illustrated in Figure 206.

When the cowling leaves the cylinders exposed, the shape of the nose and the projection of the cylinders, cause the airflow to leave the surface of the fuselage. When the Venturi Cowling is applied (as in Figure 206 (b), the flow is smoothed out and the air is made to follow the contour of the fuselage.



Townend Ring

FIGURE 205

Resistance of Free Air Radiators

Where a nose radiator is employed, with the engine in back of the radiator, it is very difficult to give rules for the increase in radiator resistance due to the fuselage.

Where a free air radiator is employed, a resistance coefficient of .0026 pounds per square foot of normal area per mile per hour is reasonable.

Tail Surfaces

For estimating tail surfaces resistance, the Army Air Corps recommends a figure of .00006 pound per square foot of surface per mile per hour. This coefficient takes care of tail plane brace wires and struts.

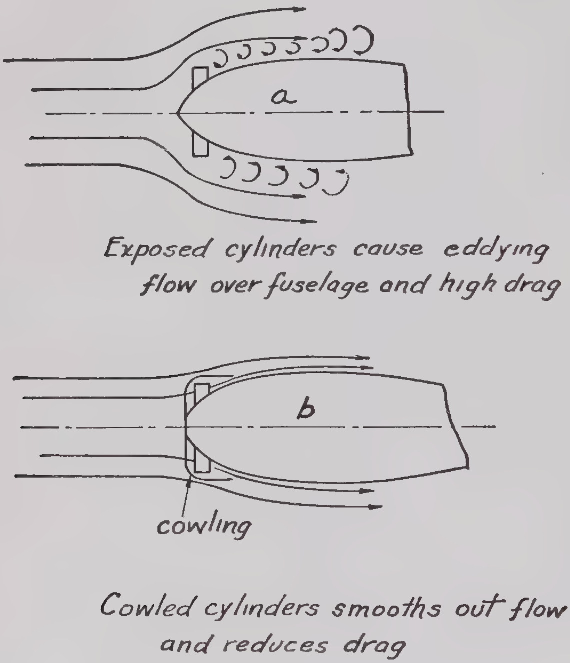


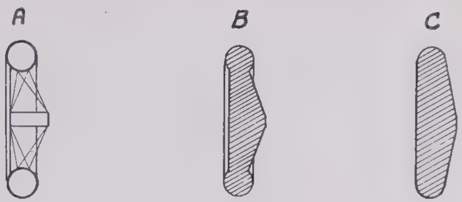
FIGURE 206

Resistance of Wheels

The values employed by the Army Air Corps for computing the resistance of wheels are given in Figure 207.

An Example of Resistance Estimation

In Figure 208 is shown the design of August Zinnser, Jr.,



Tire Size	A Bare Wheel	B Usual Fairing	C Full Fairing
20 x 2	.00061	.000406	.000203
26 x 3	.00108	.00072	.000360
28 x 4	.001410	.00094	.000470
30 x 5	.001815	.001210	.000605
32 x 6	.002285	.001525	.000761
36 x 8	.003380	.002250	.001125
44 x 10	.005120	.003410	.001705
54 x 12	.007590	.005060	.00253

FIGURE 207

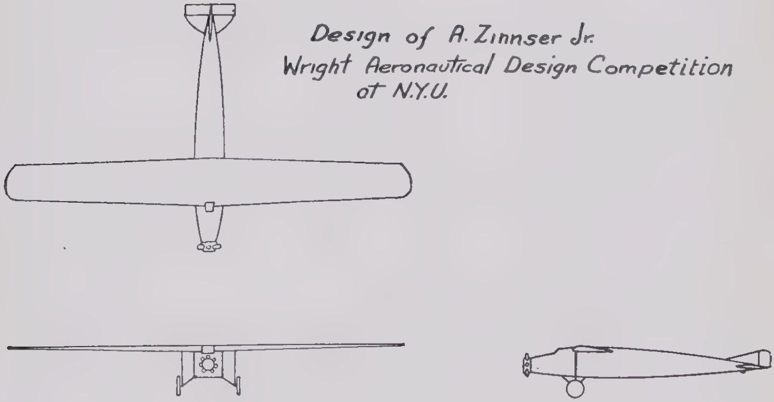


FIGURE 208

which won the Wright Aeronautical Corporation's 1929 Design Prize for aeronautical students at New York University.

The estimate of Parasite Drag and Horse-Power Required was obtained by means of the following table:

H. P. REQUIRED BY PARASITE DRAG

$$H\ P = \frac{K\ V^3}{375}$$

V	V^3	$K\ V^3$	H. P.
40	64000	1729	4.61
50	125000	3378	9.00
60	216000	5835	15.56
70	343000	9262	24.70
80	512000	13830	36.89
90	729000	19700	52.54
100	1000000	27016	72.00
110	1331000	35860	95.60
120	1728000	46690	124.40

From the known characteristics of the airfoil and the above Parasite Drag data, the horse-power required curves of Figure 209 were obtained.

The most striking lesson to be derived from these curves is the importance of the parasite drag at high speeds. At 73.2 miles per hour the parasite horse-power curve crosses the wing horse-power curve, and thereafter increases at a much more rapid rate than the wing horse-power.

This is quite a typical condition and indicates that for high speed performance reduction in parasite drag is likely to be a much more important factor than improvement in airfoil design. A confirmation of this statement is also to be found in the fact that the parasite drag at 1 mile per hour is greater than the minimum wing drag on a basis of 1 mile per hour.

It is also interesting to see what a large proportion the land-

Part	No.	Size	Coef.	Drag at 1 mph
Fuselage Chassis..	1	Cross Sectional Area = 15.6 sq. ft. $D = Kx\ AV^2$ $A = 15.6$ $V = 1$	Kx = .000753 lbs./ft.^{2}/mph	.011740
Front Struts...	2	Assume F.R. = 3 with fairing D per ft. = K x d″ x V^2 D = 2.5″ L = 3.5 (projected) +3.0 for two end fittings = 6.5′	K = .0000183 lbs./ft.^{2}/mph	.000460
Rear Struts	2	Assume F.R. = 3 with fairing D per ft. = K x D″ x V^2 D = 2.5″ L = 4.0 (projected) +3.0 for two end fittings = 7.0′	K = .000183 lbs./ft./mph	.000460
Shock Absorber Struts.....	2	Assume F.R.. = 3.5 with fairing D per ft. = K x D″ x V^2 D = 2.5″ L = 3.0′ (projected) +3.0′ for two end fittings = 6.0′	K = .000183 lbs./ft./mph	.000540
Shock Absorber Unit....	2	Assume F.R. = 2.5 with fairings D = 3.5″ L = 3.0′ no end fittings	K = .0000194 lbs./ft./ mph	.000270
Wheels....	2	30″ x 5″	D = .000605 lbs./mph	.001210
Tail Surfaces....		Area 36 sq. ft.	K = .00006 lbs./ft.^{2}	.00216
Tail Wheel and Support....		Approximated		.0003
Control horn	4		.0010 lbs./mph	.0040
Lights and Exhaust...		Approximated		.0032
				.024560
Interference of Parts...		Add 10%		.002456
				.027016

ing gear drag bears to the fuselage drag, namely, 26.9%. The use of a retractible landing gear is evidently well worth while.

It will be noted that Mr. Zinnser in making his computations neglected the effect of slipstream.

To correct for slipstream, the following procedure is followed:

(a) The thrust of the propeller at any speed is obtained either from wind tunnel tests or by calculation, or from conventional propeller characteristic curves.

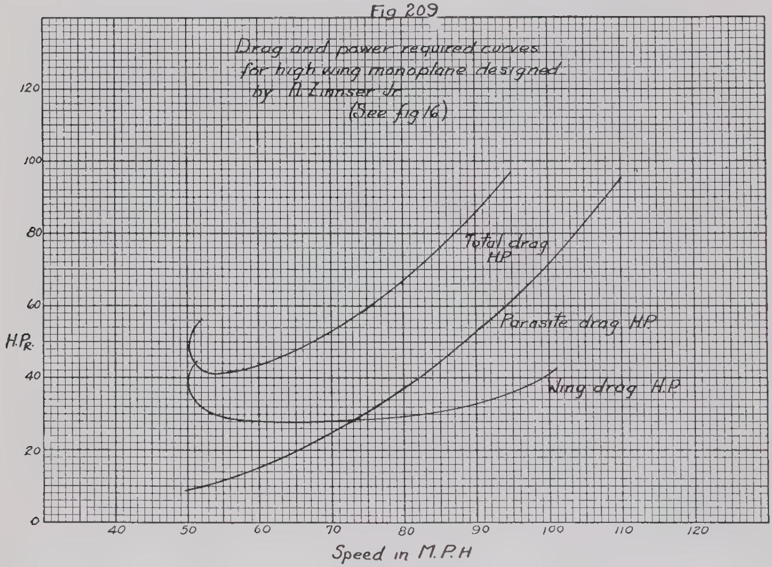


FIGURE 209

(b) The thrust of the propeller is equated to the momentum imparted to the air per second as it passes through the circular area swept out by the propeller, and hence the slipstream velocity is found.

(c) If V is the speed of the airplane and v is the extra velocity imparted to the air as it passes through the propeller disk area then the resistance of any part in the slipstream is multiplied by the ratio $\dfrac{(V + v)^2}{V^2}$

However, many designers are of the opinion that the error in neglecting slipstream effects is negligible and this view if substantiated by some wind tunnel tests. It is true that the slipstream increases the parasite resistance. But at the same time the presence of resistance producing objects behind the propeller, retards the speed. One factor entering into the efficiency of the propeller is the ratio $\frac{V}{V + v}$ and increase in this ratio improves the efficiency of the propeller as compared with its efficiency in free air. One effect counterbalances the other.

Possibilities of Parasite Drag Reduction

The study of airplane parasite drag is one on which much attention is being concentrated at the moment, both in the wind tunnel and in full flight work. Space will not permit us to go into details, but the following suggestions may perhaps help the reader in his further studies or experiments.

1. Improvement and simplification of the cowling of the radial air-cooled engine both when placed in the nose of a fuselage, and on the wings. The Townend ring, because of its simplicity, is particularly interesting.

2. Improvement in the cowling of in-line air-cooled engines. An obvious line of attack is to cowl the engine in almost completely, with the smallest opening or scoop at the front end, and then to guide the air by vanes inside the cowling so as to give each cylinder the proper amount of air for cooling.

3. Improvement in the interference between engines, nacelles and wing, in outboard engines. The wing is particularly sensitive to disturbances at or above its upper surface. Air-cooled engines placed in nacelles only a little distance above the wing, bring down the Lift/drag ratio far more than would appear to be the case were the drag of the wing and the drag of the engine and nacelle simply added together. A great deal of work remains to be done in reducing interference, whether by placing the nacelle well above the wing, or by placing the nacelle below the wing, or by putting the nacelle at the leading

edge of the wing with such careful cowling and streamlining that the nacelle becomes an integral part of the wing. (See Figure 210.)

4. Employment of cantilever monoplane wing, skillfully tapered in both plan and thickness, so as to provide width of chord and depth at the root. With such wings all external bracing will disappear, and at the same time the fuselage begins to disappear in the wing, thus bringing nearer the conception of a flying wing. In the Northrup Monoplane, recently flown and described in the technical press, a short nacelle displaces the conventional fuselage with the tail surfaces sup-

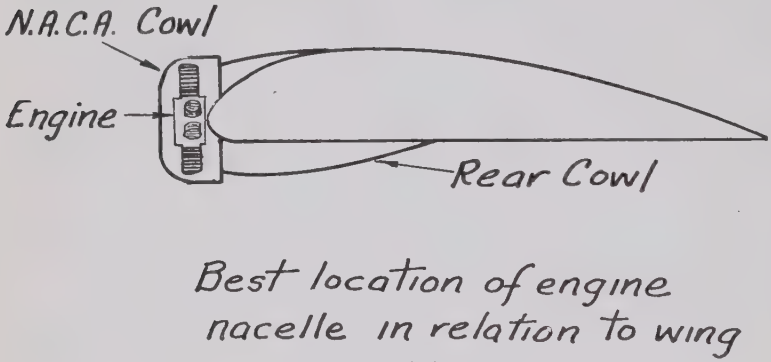


FIGURE 210

ported on outriggers. The nacelle, in which the pilot sits and a pusher engine is mounted, is seen from the diagram of Figure 211 to have disappeared almost completely into the wing.

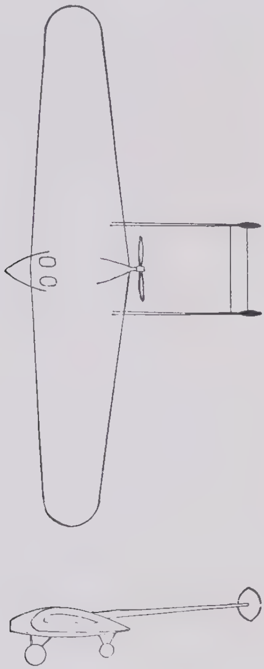
5. The use of pusher instead of tractor propellers. In the Northrup Monoplane a pusher mounted at the end of a long shaft is substituted for the conventional tractor propeller. No resistance producing parts thus appear in the slipstream. Perhaps there is indeed advantage in such an arrangement.

6. The use of careful filleting between fuselage and wings (see Figure 212). This decreases the interference between wing and fuselage. The filleting should be neither too large nor too

small, however. Filleting between struts and fuselage and struts and wing should also be useful.

7. The use of inclined wing struts of lifting section.

8. Careful attention always to the possibility of interference as between chassis struts meeting at a small angle, etc.



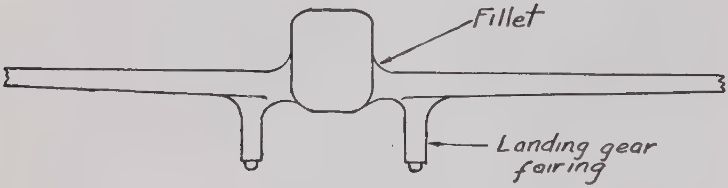
Northrop Flying Wing

FIGURE 211

9. The streamlining of landing wheels with parts and alternatively the use of retractible chassis.

Many other possibilities will suggest themselves to the reader. There is no doubt that in the reduction of airplane drag there

lies a most fruitful field for the aerodynamicist and the airplane designer.



Wing and chassis fairing a low wing monoplane

FIGURE 212

Problems

1. What would be the drag of a round cylinder 3″ in diameter and 4 feet long in an air stream of 70 m.p.h.?

   Answer: 15.6 pounds.

2. What would be the resistance of a stranded wire ½″ in diameter and 6 feet long at an air speed of 100 m.p.h.?

   Answer: 9.54 pounds.

3. What would be the resistance of a round wire ½″ in diameter and 6 feet long at an air speed of 100 m.p.h.?

   Answer: 7.95 pounds.

4. What would be the resistance of a Navy No. 1 strut 1 inch in diameter and 6 feet long at 100 m.p.h.

   (a) Of finess ratio 3
   (b) Of finess ratio 2
   (c) Of finess ratio 4

   Answer: (a) = 1,098 pounds.
   (b) = 1,485 pounds.
   (c) = 1,210 pounds.

5. What would be the drag of the struts in problem (4) if they were tilted at an angle of 60° to the wind?

Answer: (a) 951 pounds.
(b) 1,285 pounds.
(c) 1,049 pounds.

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Y

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The WRIGHT AERONAUTICAL CORPORATION, Paterson, New Jersey, builders of the famous *"Whirlwind"* engine, say:

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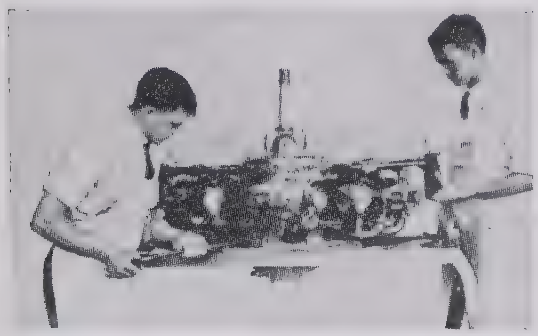

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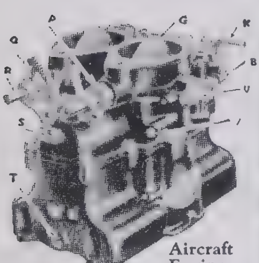

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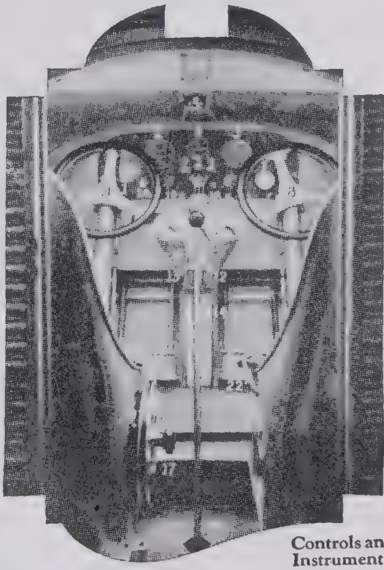

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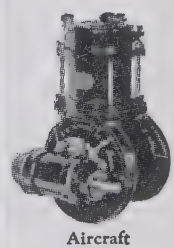

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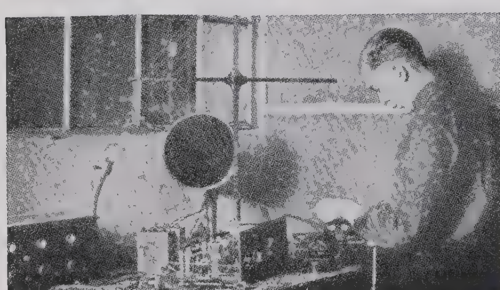

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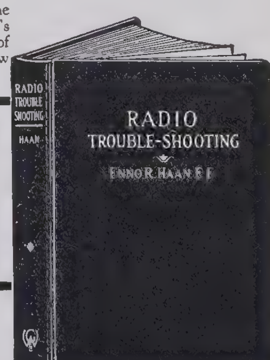

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